DOCUMENTS SECTION

COMMONWEALTH OF PENNSYLVANIA

DEPARTMENT OF INTERNAL AFFAIRS

TRENTON AND SUB-TRENTON OF OUTCROP AREAS IN NEW YORK, PENNSYLVANIA AND MARYLAND

By

FRANK M. SWARTZ

TOPOGRAPHIC AND GEOLOGIC SURVEY

BULLETIN G 22

1948

PENNSYLVANIA
GEOLOGICAL SURVEY
FOURTH SERIES

BULLETIN G 22

TRENTON AND SUB-TRENTON OF OUTCROP AREAS IN NEW YORK, PENNSYLVANIA AND MARYLAND

By
FRANK M. SWARTZ

Reprinted from
BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 32, NO. 8, PP. 1493-1595

DEPARTMENT OF INTERNAL AFFAIRS
WILLIAM S. LIVENGOOD, JR., *Secretary*

TOPOGRAPHIC AND GEOLOGIC SURVEY
S. H. CATHCART, *Director*

1948

Digitized by the Internet Archive
in 2016 with funding from
This project is made possible by a grant from the Institute of Museum and Library Services as administered by the Pennsylvania Department of Education through the Office of Commonwealth Libraries

https://archive.org/details/trentonsubtrento00swar

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 32, NO. 8 (AUGUST, 1948), PP. 1493-1595, 26 FIGS., 3 TABLES

TRENTON AND SUB-TRENTON OF OUTCROP AREAS IN NEW YORK, PENNSYLVANIA, AND MARYLAND[1]

FRANK M. SWARTZ[2]
State College, Pennsylvania

ABSTRACT

Trenton and sub-Trenton rocks of the outcrop regions in New York, Pennsylvania, and Maryland are described, and their conditions of origin and paleogeography are discussed. The basement rocks are considered with respect to regional characters, possible causes of magnetic and isostatic anomalies, and relation to deformation of the Paleozoic sediments. New stratigraphic charts, and new isopachous and paleogeographic maps are presented for the Glenarm, the Lower Cambrian, the Middle and Upper Cambrian, the Lower Ordovician, and the Middle Ordovician sediments of the region, with accompanying discussions of the stratigraphy, regional relations, and sedimentation of the deposits. Brief consideration is given to relations of the Trenton and sub-Trenton at the outcrop in New York, Pennsylvania, and Maryland, with respect to search for oil and gas in the more westerly subsurface areas of these sediments.

Introduction

Trenton and sub-Trenton Paleozoic strata reach the surface in New York, Pennsylvania, and Maryland, along the following belts of outcrop (Fig. 1).

1. New York
   a. Flanks of Adirondack Mountains
   b. Hudson River Valley
2. Pennsylvania and Maryland
   a. Limestone valleys and quartzite hills southeast of Triassic Lowland, and possibly in Glenarm region
   b. South Mountains, Reading Prong, and Great Valley, north and northwest of Triassic Lowland
   c. Anticlinal valleys of Ridge and Valley Province

In New York, Trenton and sub-Trenton Paleozoic strata have been studied especially by H. P. Cushing, Rudolf Ruedemann, G. Van Ingen, P. E. Raymond, G. M. Kay, and W. J. Miller; in Pennsylvania and Maryland, extensive work has been done by G. W. Stose, A. I. Jonas, R. S. Bassler, Charles Butts, Ernst Cloos, G. M. Kay, and B. L. Miller. (See papers by these and other authors, listed in appended bibliography.) The present discussion represents an attempt to bring together and correlate in summary fashion data made available by these and other geologists and to give consideration to problems of stratigraphic relations, conditions of deposition, and factors affecting oil and gas accumulation and exploration. No new field investigations have been made; but new stratigraphic charts and new, preliminary ispachous maps have been prepared from the published accounts.

Order of Discussion

The discussion of the Trenton and sub-Trenton rocks of the outcrop regions in New York, Pennsylvania, and Maryland is arranged under the following major headings.

[1] Published by permission of the State Geologist of Pennsylvania and of the Dean, School of Mineral Industries, The Pennsylvania State College. Manuscript received, May 17, 1948.

[2] Chief, Division of Geology, The Pennsylvania State College.

Pre-Cambrian basement
Lower Cambrian
Middle and Upper Cambrian
Lower Ordovician
Middle Ordovician Chazyan deposits
Middle Ordovician Black River and Trenton deposits
Relations of Trenton and sub-Trenton at outcrop in New York, Pennsylvania, and Maryland, with respect to search for oil and gas in subsurface areas farther west

Each of these major topics is further subdivided. Areal geologic maps, stratigraphic charts, and preliminary isopachous maps accompany and illustrate the text material.

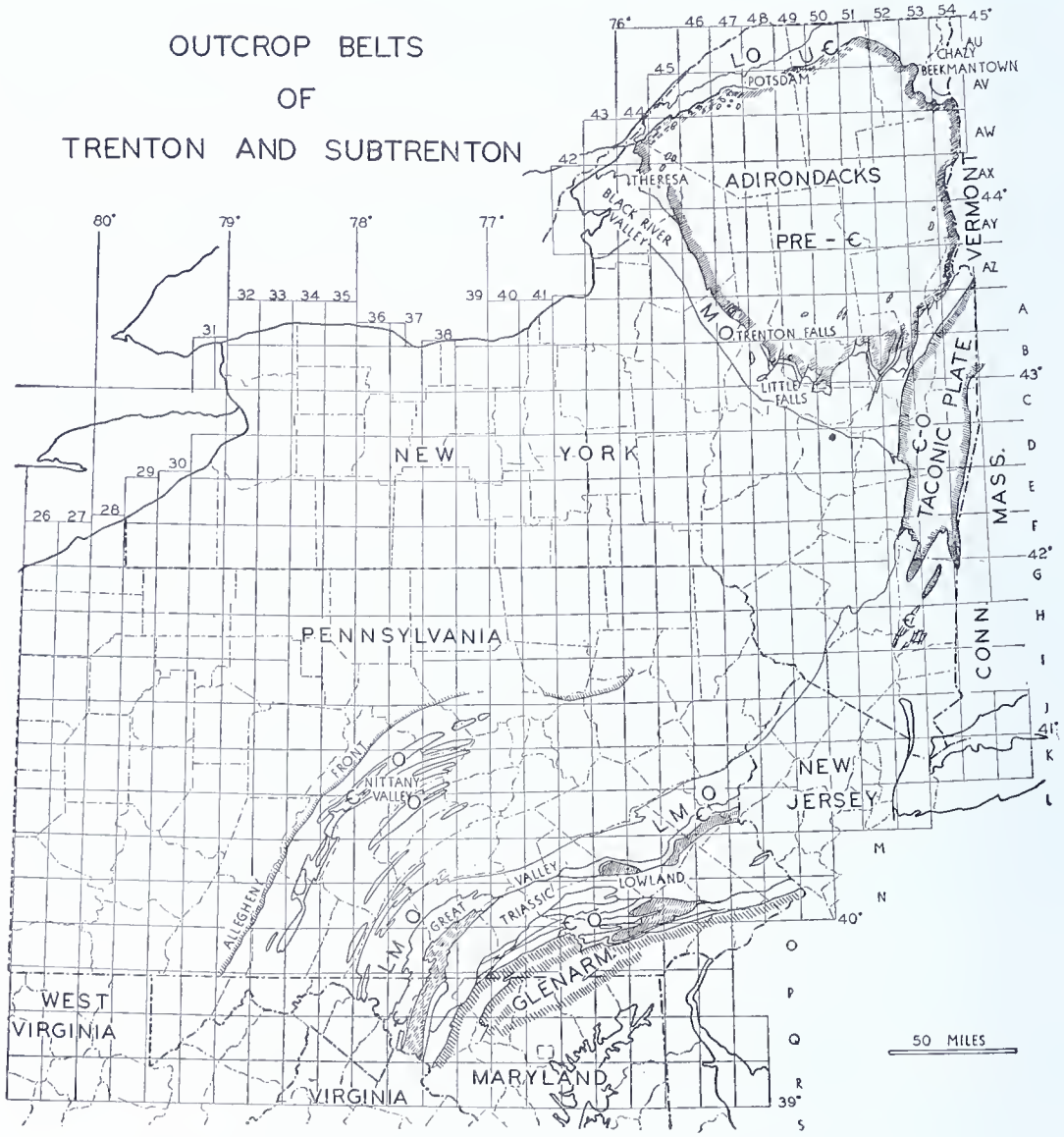


FIG. 1.—Index map illustrating areal geology of Trenton and sub-Trenton in New York, Pennsylvania, and Maryland.

Pre-Cambrian Basement

GENERAL CONSIDERATIONS

The pre-Cambrian basement of Pennsylvania, Maryland, and New York has no promise either for reservoir sites for oil and gas occurrence, or as the source for petroliferous materials of present-day oil and gas accumulations. Nevertheless, the basement and its rocks are of interest in considering the oil and gas relationships of the Trenton and sub-Trenton strata of the region because, first, they must have furnished materials of which some of the early Paleozoic deposits are composed; second, their surface relief doubtlessly affected to some degree the distribution and characters of the initial Paleozoic sediments laid upon them; third, the basement may have had structural trends significant in determining the geography of Paleozoic sedimentation; fourth, the basement rocks presumably took part in transmission of forces by which Trenton and sub-Trenton strata were deformed subsequent to their deposition; fifth, magnetic and gravimetric investigations attempting to deal with deep structures must take into account the inherent complexity of the pre-Cambrian rocks physically as well as chemically.

Too little is known of the pre-Cambrian of the region to afford full analysis of any one of the listed relationships. Nevertheless, it appears profitable to review known features of the pre-Cambrian in its regions of outcrop, in an attempt to secure helpful clues. Relief of surface of the pre-Cambrian complex, and other relations to Paleozoic deposits, will generally be considered in discussions of appropriate Cambro-Ordovician sediments.

AREAL DISTRIBUTION OF PRE-CAMBRIAN OUTCROPS

Rocks of accepted pre-Cambrian age are widely exposed in New York in the Adirondack Mountains, and are found in limited areas in the southern part of the Hudson River Valley. In Pennsylvania and Maryland, pre-Cambrian terranes are exposed: first, in the Reading Prong and Honeybrook Upland, north and south, respectively, of the Triassic Lowland in eastern Pennyslvania; second, in the South Mountains just west of the Triassic belt in south-central Pennsylvania and the adjacent part of Maryland. In a third region, southeast of the Martic Line, there are widespread Glenarm metamorphics whose possible pre-Cambrian age has given rise to vigorous controversy.

The pre-Cambrian masses of each of these areas are briefly considered.

PRE-CAMBRIAN OF ADIRONDACKS

The pre-Cambrian rocks of the Adirondacks include in order of increasing age the following main masses, according to Buddington (1939).

(Subordinate diabase dikes and some gabbros)

(5) Granite series
(4) Pyroxene quartz syenite and granite series
(3) Diorite series

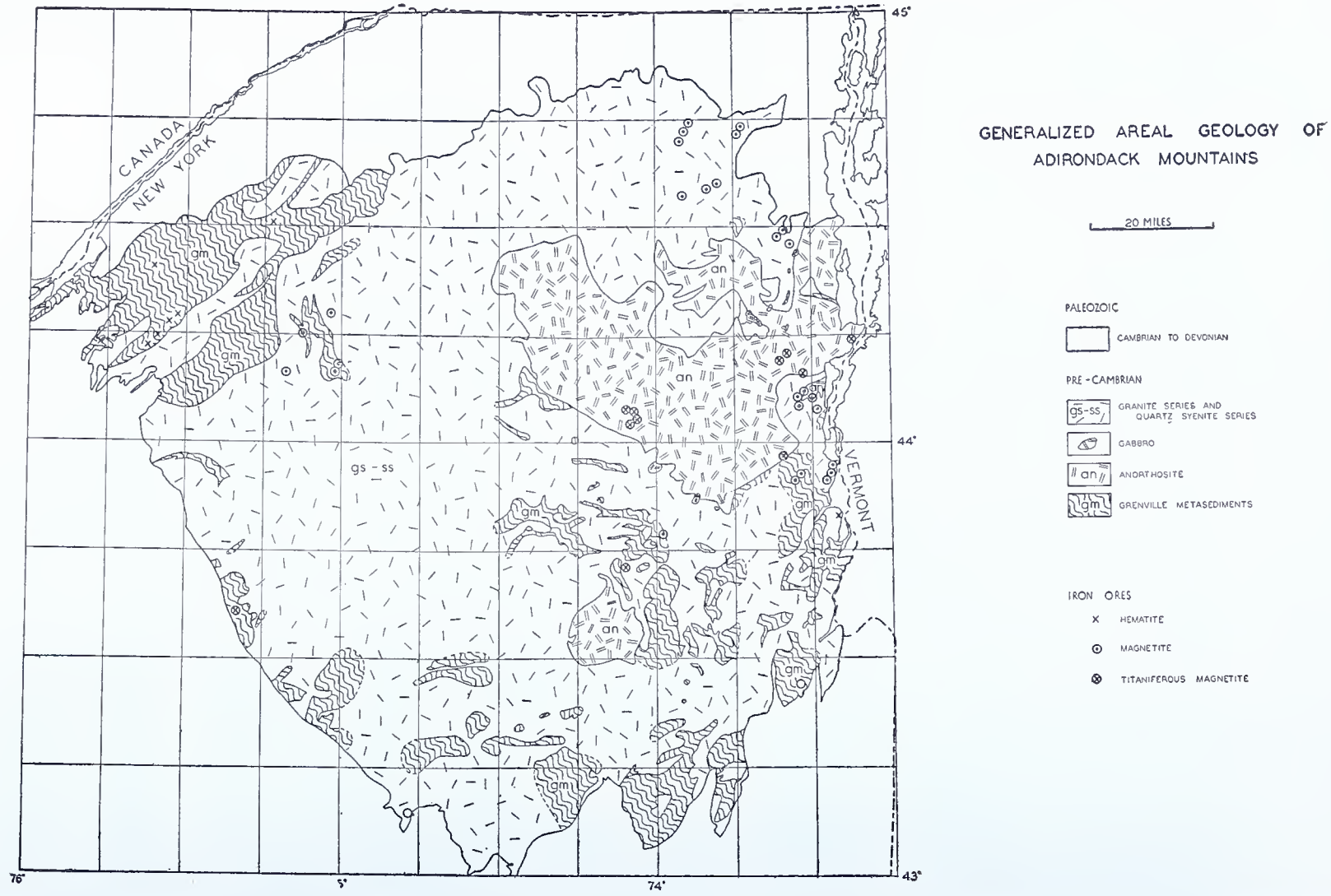


FIG. 2.—General areal geology of pre-Cambrian of Adirondack Mountains.

(2) Anorthosite series, with associated gabbro and metagabbro (Local granites; pre-anorthosite age not well established)
(1) Grenville series, consisting of coarse-textured marbles, quartzites, schists, amphibolites, migmatites

The larger features of the areal geology of the Adirondacks are illustrated in Figure 2. The granite and syenite series (4 and 5 of Buddington's list) are widely exposed. They occur in part as large stocks and batholithic masses, in part as smaller bodies intricately penetrating the Grenville metasediments. The diorite series (3) is subordinate, and local in its occurrence. The anorthosite (2) occurs in a major massif in the eastern Adirondacks, where it helps to produce some of the most rugged relief of the mountain area. A smaller body of the anorthosite occurs farther south. The marginal parts of the anorthosite tend to be somewhat gabbroic, and local, small bodies of gabbro are associated with the massif. The ancient Grenville sediments (1), originally believed to be continuous across the Adirondack region, have been intruded, sharded, and affected by the intrusive complexes so that their remnants are limited in extent, strongly metamorphosed, and pass at many places into migmatitic rocks containing large proportions of igneous materials.

Superimposed upon this larger pattern there is a wealth of smaller features. Buddington (1939) has illustrated many types of geologic complexities that have resulted from invasion of successive igneous intrusions into the ancient Grenville sediments and into each other. In part the syenite and granite intrusions occur along fold axes of the Grenville, in a fashion to complement axial thickening of the strata.

Before deposition of the Cambrian strata of the region, the pre-Cambrian rocks were deeply truncated by erosion. The Cambrian sediments were spread over a surface of low relief that had not only cut across the granite-intruded folds of the Grenville rocks, but had also uncovered presumably deep-seated intrusive masses of the granite, syenite, and anorthosite series.

Significant bodies of iron ore occur in the pre-Cambrian of the Adirondacks, and in general are associated with Grenville remnants. Locations of important concentrations of hematite, magnetite, and titaniferous ores are plotted in Figure 2 after Newland (1908).

The pre-Cambrian of the Adirondacks is complex in its geophysical as well as geologic characters. Local concentrations of magnetite ore produce strong magnetic effects, illustrated in Figure 3 by an isogammous map of the Benson mine area of the Oswegatchie Quadrangle, simplified from aero-magnetic *Preliminary Map 1, Geophysical Investigations, United States Geological Survey* (1946). Along the belt of Grenville metasediments and associated microcline granite gneiss in which the Benson Mines are located, magnetic values measured at 1,000 feet above surface vary from minus 700 to plus 3,500 gammas. There is little magnetic relief over near-by areas of hornblende granite gneiss; but approximately 10 miles west of Benson Mines a belt of quartz syenite furnishes a 1,500-gamma high, presumably again due to increased magnetite content.

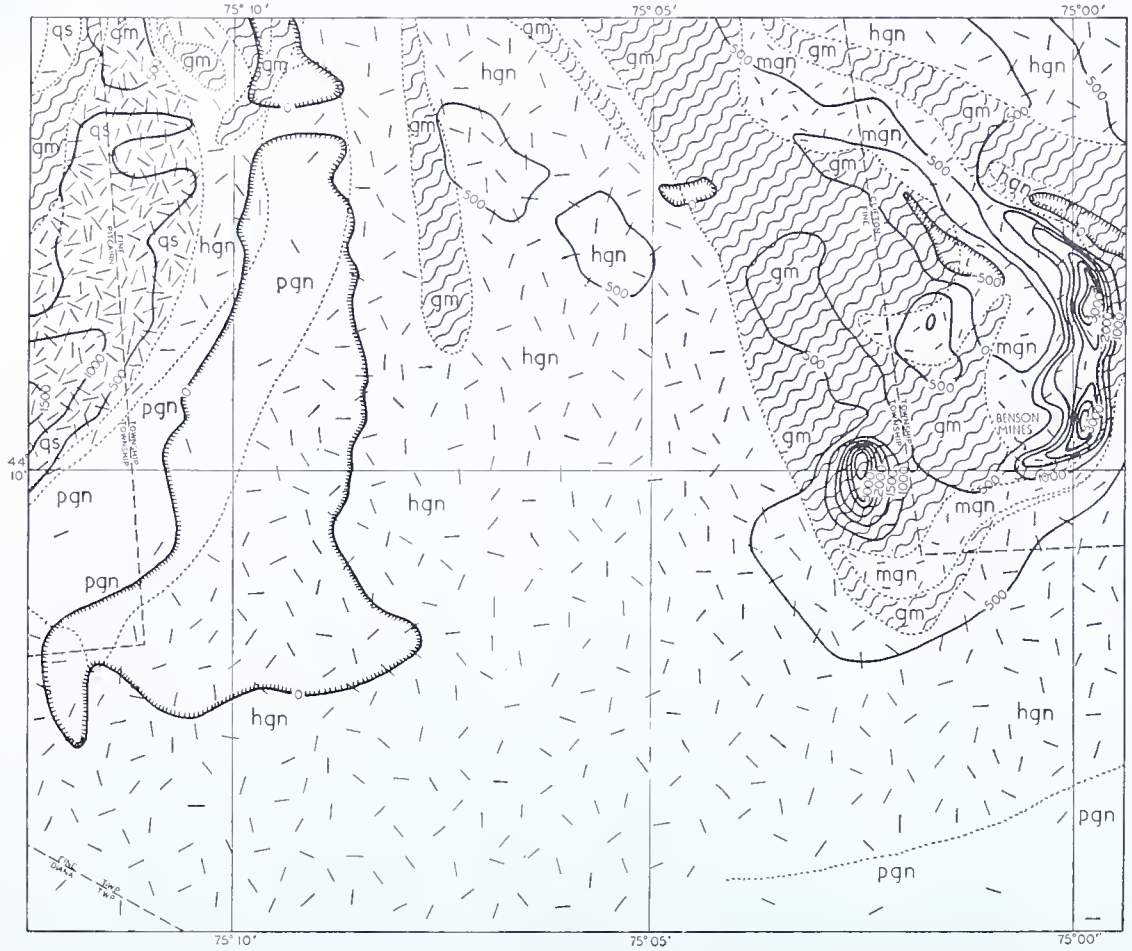


FIG. 3.—Areal geology and magnetic anomalies of Benson Mine area of Oswegatchie Quadrangle, New York. Simplified from *Preliminary Map 1, Geophysical Investigations, United States Geological Survey.*

The Benson Mine map suggests that where a pre-Cambrian complex such as that of the Adirondacks is buried beneath younger sediments, the magnetic variations due to changing magnetic susceptibilities of the constituent members may greatly outweigh variations due to relief of the buried surface of the complex. Large bodies of magnetite ore, such as occur at various localities in the pre-Cambrian of the Adirondacks (Fig. 2), would produce marked magnetic anomalies even where buried below several miles of sediments. More moderate percentages of magnetite, if disseminated through large rock masses, would likewise produce

TABLE I

RANGES IN PERCENTAGE OF MAGNETITE AND ILMENITE IN SAMPLES OF ADIRONDACK ROCKS (Buddington, 1939)

Rock Type	*Number of Determinations*	*Percentage Magnetite (Norms)*	*Percentage Ilmenite (Norms)*
Grenville amphibolite	2	4.4–4.9	3.3–4.3
Pitcairn gneiss complex	2	1.4–6.3	0.8–1.1
Anorthosite of main massif	5	0.9–2.0	0.4–3.0
Gabbroic anorthosite, and norite and gabbro areas of anorthosite massif	11	0.8–4.9	Trace-13.1
Rocks from anorthosite-Grenville contact zones	10	Trace–5.1	Trace–6.9
Metagabbros of northwestern and eastern Adirondacks	19	1.6–7.2	0.6–9.7
Rossie diorite	5	0.9–8.7	Trace–6.0
Quartz syenites of Diana, Santa Clara, and other complexes	34	Trace–11.1	Trace–8.1
Hornblende granite	5	1.4–4.2	Trace–1.0
Herman and Antwerp granites	10	0.2–3.5	Trace–1.5

significant anomalies. To exemplify normal variations in magnetic qualities of several rock types, Tables I and II have been prepared, summarizing respectively Buddington's (1939) records of magnetite and ilmenite in rock samples from the Adirondacks, and Birch's (1942) data on the general variations of magnetic susceptibility in common rock types.

Significant gravimetric as well as magnetic variations can be expected in such rocks as those that compose the pre-Cambrian of the Adirondacks. Density determinations for Adirondack specimens have not been obtained. However, some guide to the order of magnitude of expectable differences in density, and thus of gravimetric variations, is furnished in Table III from data given in the *Handbook of Physical Constants* (Birch *et al.*, 1942).

PRE-CAMBRIAN OF READING PRONG AND HONEYBROOK UPLAND OF EASTERN PENNSYLVANIA

Pre-Cambrian rocks are exposed in eastern Pennsylvania in the Reading Prong of the Jersey Highlands, just north of the Triassic Lowland, and also in the Honeybrook Upland which adjoins the Triassic on the south (Figs. 4, 5).

The pre-Cambrian rocks of these eastern Pennsylvania areas consist of ancient, highly deformed gneisses of sedimentary origin, intruded by stock-like, plutonic masses of gabbro, anorthosite, and granitic rocks.

TABLE II

VARIATIONS IN MAGNETIC SUSCEPTIBILITY IN COMMON ROCK TYPES
(*Handbook of Physical Constants* (Birch *et al.*, 1942)

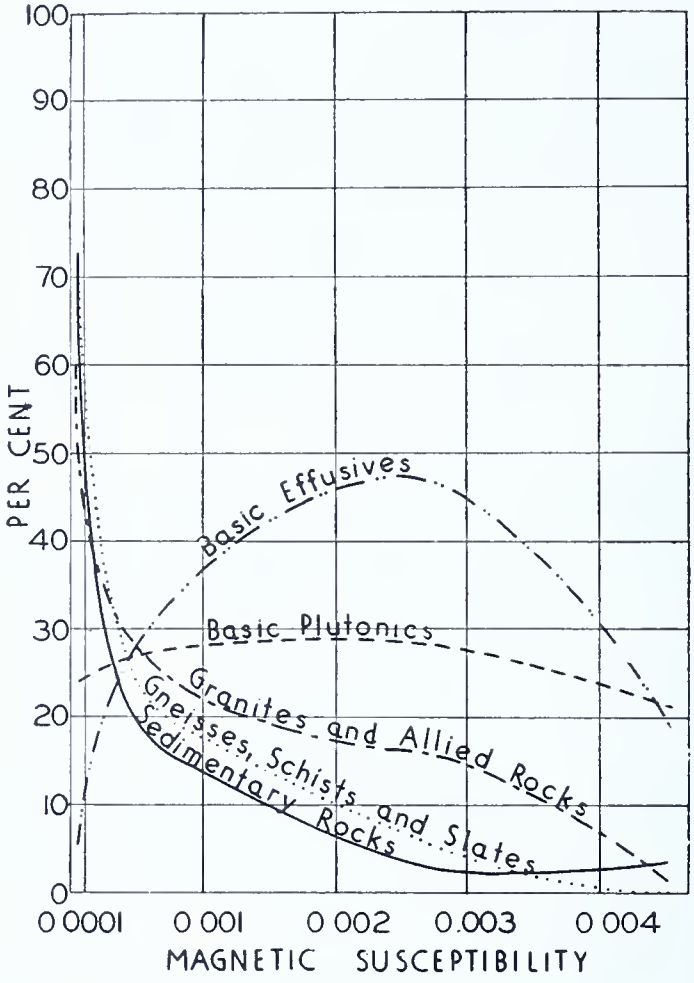


TABLE III

DENSITIES OF MINERALS AND ROCK TYPES
(*Handbook of Physical Constants* (Birch *et al.*, 1942)

Mineral Species or Rock Type	*Number of Samples*	*Average Density*	*Range in Density*
Magnetite			4.97–5.18
Quartz		2.654	
Quartzite	2	2.555	2.48–2.63
Calcite		2.717	
Marble	34	2.76	2.66 –2.86
Granite	155	2.667	2.516–2.809
Syenite	24	2.757	2.630–2.899
Diorite	13	2.839	2.731–2.960
Gabbro and diabase	67	2.970	2.803–3.120
Anorthosite	12	2.734	2.640–2.920
Pyroxenite and peridotite	11	3.233	3.10 –3.318

The pre-Cambrian complexes were deeply truncated by erosion prior to the time when Lower Cambrian sediments were spread upon them. Mapping of the Cambrian-pre-Cambrian boundary suggests that the erosion surface was well peneplaned.

The pre-Cambrian rocks and rock-history of the Reading and Honeybrook uplands are thus comparable with those of the pre-Cambrian of the Adirondacks in sedimentary-plutonic succession, in metamorphism and general structure, and in deep erosional truncation preceding deposition of the Cambrian. They furthermore are probably comparable with the pre-Cambrian rocks of the Adirondacks in their variations in magnetic and gravimetric properties.

Structurally, the rocks of the Reading Prong and Honeybrook Upland are of further interest because they provide the main exposures, in the Pennsylvania-New York area, of the Cambrian-pre-Cambrian boundary surface where affected by folding of the Paleozoics. Of special interest is the problem: did the Paleozoics, at the time of their deformation, shear across the pre-Cambrian basement so that their folds are in general discordant with the pre-Cambrian surface? Or did the pre-Cambrian mass yield in reasonable accord with at least the more significant structures of the Paleozoics? Relations observed here where the surface of the pre-Cambrian is uncovered, may provide some guide to probable conditions farther west and northwest where the pre-Cambrian is deeply buried.

From the published areal geology maps of the Reading Prong and more especially of the Honeybrook Upland area, it appears that the pre-Cambrian mass did not remain neutral to the folding, and that the Cambrian-pre-Cambrian junction did not act as a plane of weakness, above which the Paleozoics sheared so that their major as well as minor structures became independent of the pre-Cambrian surface. Rather, the pre-Cambrian complex yielded to the forces that deformed the Paleozoics, and such yielding may have been a significant factor in development of the folds of the Paleozoics.

The most striking example in the area to show adjustment of the pre-Cambrian basement to a fold of the overlying Cambro-Ordovician strata occurs in the Mine Ridge anticline extending southwestward from the main part of the Honeybrook Upland (Fig. 5). This is a large and comparatively simple arch, in which the surface of the pre-Cambrian rocks rises in consonance with the curvature of the Cambro-Ordovician strata. The southern limb is steeper than the northern limb, so that the axial plane dips northward as it does in adjacent folds.

The near-by Welsh Mountain anticline is much disturbed by faults, so that it does not form a smooth arch. Nevertheless, the irregularity is apparently not due to special weakness and consequent shearing along the Cambrian-pre-Cambrian surface; instead, the faults causing the irregularities seem to transect the Cambrian and pre-Cambrian alike, although they are somewhat more numerous in the Paleozoics than in the pre-Cambrian. (See both map and structure section, Fig. 5.)

It is reasonably clear that in the Reading Prong and Honeybrook Upland the

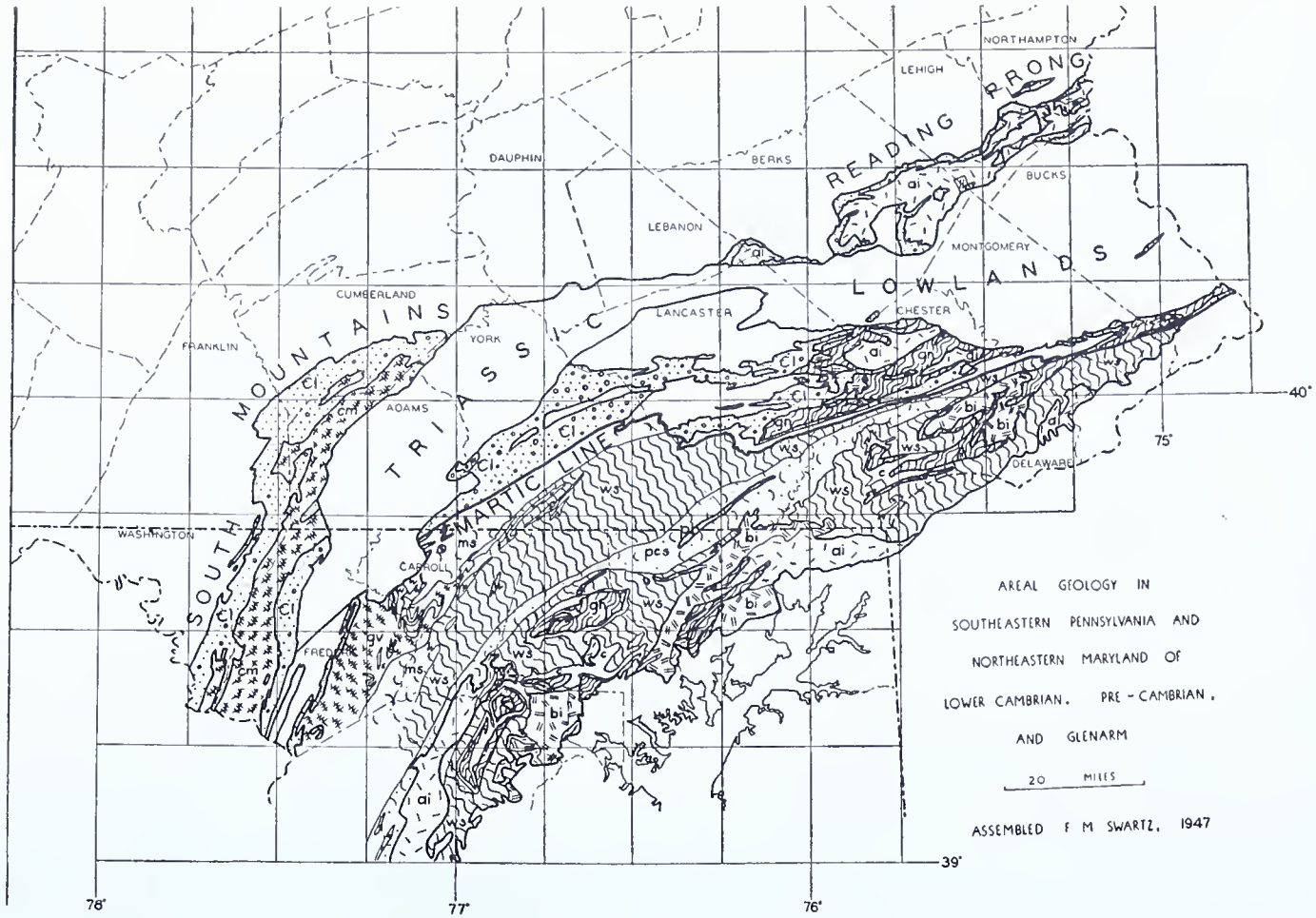


FIG. 4.—Areal geology in southeastern Pennsylvania and northeastern Maryland of Lower Cambrian and pre-Cambrian north of Martic Line, and of Glenarm and associated rocks southeast of Martic Line. Symbols are as follows, in descending order. *South Mountains:* Cl, Lower Cambrian; cm, Catoctin metavolcanics. *Reading Prong:* Cl, Lower Cambrian; ai, pre-Cambrian acidic intrusives, with small areas of other pre-Cambrian rocks. *Area between Triassic Lowland and Martic Line, including Honeybrook Upland toward east:* Cl, Lower Cambrian; bi, pre-Cambrian basic intrusives; ai, pre-Cambrian acidic intrusives; gn, Pickering sedimentary gneiss. *Glenarm area south of Martic Line:* pb, Peach Bottom slate and Cardiff conglomerate; pcs, Peters Creek schist; ws, Wissahickon schist, commonly based by narrow belts of Cockeysville marble and Setters quartzite at domes of Baltimore gneiss; gv and ms, Glenarm metavolcanics and Marburg schist, respectively, with some small areas of Wakefield and Silver Run marbles, the relations to Glenarm proper not well established; bgn, Baltimore gneiss, pre-Setters: bi, and ai, post-Wissahickon basic and acidic intrusives.

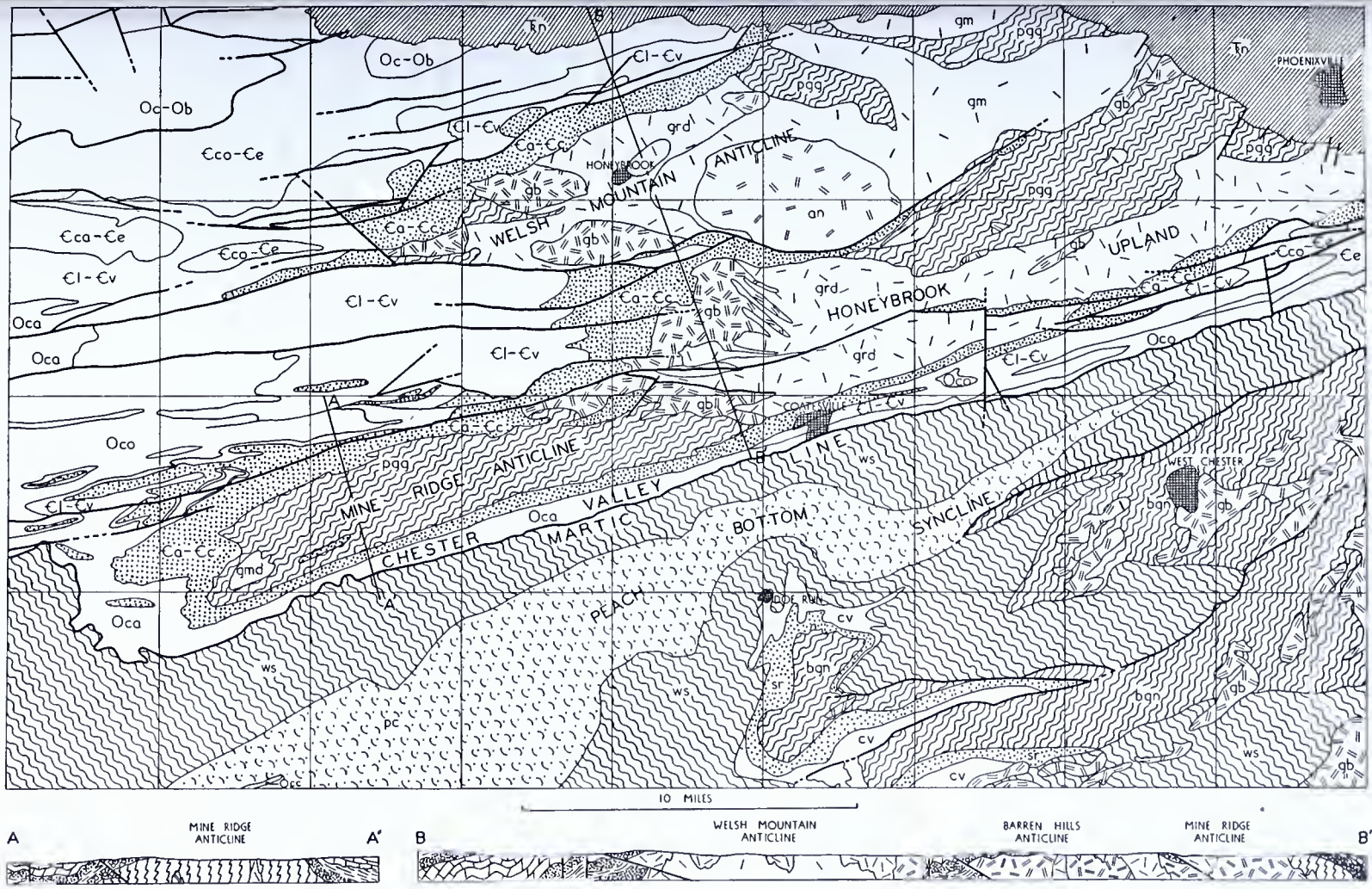


FIG. 5.—Areal geology of Trenton and sub-Trenton in Honeybrook Upland, Mine Ridge anticline, Chester Valley, and eastern part of Peach Bottom syncline, southeastern Pennsylvania. North of Martic Line: Rn, Triassic, Newark redbeds. Oc-Ob, Cocalico shale and Beekmantown limestone; Oco, Conestoga limestone; Cco-Ce, Conococheague and Elbrook limestones; Cl-Cv, Ledger, Kinzers, and Vintage dolomites; Ca-Cc, Antietam quartzite, Harpers schist, and Chickies quartzite; gb, pre-Cambrian gabbro; an, pre-Cambrian anorthosite; qm, pre-Cambrian quartz monzonite; grd, pre-Cambrian granodiorite; pgg, Pickering gneiss. South of Martic Line: Opc, Peach Bottom slate and Cardiff conglomerate; pc, Peters Creek schist; Ws, Wissahickon schist; cv, Cockeysville marble; st, Setters quartzite; bgn, Baltimore gneiss; gb, post-Wissahickon gabbro.

larger structures of the Paleozoics did not develop independently of movements in the pre-Cambrian mass; but that instead the pre-Cambrian yielded to the forces that folded the Paleozoics and may well have served to transmit a significant part of the folding stress.

These comments are not of course meant to suggest that all of the folds and faults of the Paleozoics continue into the pre-Cambrian basement. Folds and faults change form and amplitude within the Paleozoics themselves, and such changes are to be expected with some increase in approaching and crossing the pre-Cambrian surface. In the Reading Prong and Honeybrook areas, however, there is no flat-lying boundary surface at the base of the folded Paleozoics, such as that postulated for the base of Mesozoics of the Jura Mountains. The writer knows of no reason to suppose that this relationship changes in the major folds on the west and northwest.

PRE-CAMBRIAN VOLCANICS OF BLUE RIDGE PROVINCE

The South Mountains, just west of the Triassic Lowland in south-central Pennsylvania and central Maryland (Fig. 4), form the northern part of the Blue Ridge Province of the Appalachian Highlands. Various ridges and valleys are carved from a succession of 3,000–4,000 feet of arenaceous and argillaceous sediments that contains Lower Cambrian fossils near its summit. Through half or more of the South Mountains, however, the Lower Cambrian strata have been stripped away by erosion, exposing a now-metamorphosed mass of extrusive igneous flows and tuffs. Especially widespread are epidote-rich metabasaltic greenstones, named by Keith, Catoctin schist, from Catoctin Mountain along the eastern border of the South Mountain region of Maryland. Associated metarhyolites or aporhyolites are bluish gray to reddish. The metarhyolites have not been given a special formational name. Since they are, in a structural and stratigraphic sense, intimately related to and intermingled with the metabasalts, the whole volcanic terrane including the metabasalts, the metarhyolites, minor metaandesites, and thin metasediments, are with questionable license grouped for the present discussion as Catoctin metavolcanics.

The Catoctin metavolcanics in this inclusive sense are composed predominantly of modified basaltic lava flows in the present area of outcrop in Maryland, with rhyolitic flows increasing in proportionate volume along the extension of the South Mountains into Pennsylvania. Recognized andesite flows are very subordinate. Amygdaloidal blebs are found at many places. Tuffaceous deposits, some with pyroclastic fragments an inch or two in diameter, form a few per cent of the total mass.

A complex of granodiorite and biotite granite is exposed in the Catoctin belt near the Potomac River in Maryland. According to Stose and Stose (1946), the granitic complex is cut by feeder dikes of the Catoctin; hence, it is part of the basement upon which the Catoctin rocks accumulated. Margining the exposures of the granitic complex are locally identified, thin occurrences of sedimentary

quartzites and associated tuffaceous slates, which are thought by Stose and Stose to represent the initial materials of the Catoctin series; at one place there is a small body of marble at this stratigraphic position. Metabasalts adjoin and appear to rest on these metasediments, or, where the latter are absent, lie directly against the granite complex. Farther north, where the metarhyolites are plentiful, it is not clear whether the metarhyolites in general lie stratigraphically above or chiefly occur below the metabasalts. To some degree, at least, bodies of the metarhyolites and metabasalts interfinger with one another.

The whole Catoctin mass has undergone low-grade metamorphism, so that there is a pervasive schistosity that dips southeastward at an angle of approximately 60°. The same schistosity affects Lower Cambrian sediments of the South Mountains region, and hence was not produced in pre-Cambrian time (Cloos, 1940).

The metamorphic crystals of the Catoctin mass are very fine-grained. Nevertheless, there is sufficient masking of original structures so that it is difficult under the conditions of soil and forest cover to follow individual flows and to establish the succession and thicknesses of members of the mass. Judging from the areal extent of the metavolcanics, and supposing that their structural complexity is comparable with that of the adjacent Paleozoics, one may estimate that the thickness of the volcanic succession reaches a maximum of at least a mile.

Mapping in the Fairview Quadrangle (Stose and Bascom, 1929) of some minor, locally traceable divisions of the metavolcanics suggests that there is a low-angle unconformity at the contact of the lavas with the Loudoun formation at the base of the Cambrian sediments. Such erosion may explain variations in Maryland in distances across the metavolcanics from the base of the Loudoun to the plutonics believed by Stose and Stose to underlie the Catoctin. Furthermore, the Loudoun sediments at places were derived principally from metarhyolites of the Catoctin series, and elsewhere in Maryland and Virginia came largely from granitic rocks such as those associated with the Catoctin. All of these relationships suggest that there was at least local erosion of the Catoctin before and during Loudoun time. Keith (1894) thought it probable that in northern Virginia the pre-Loudoun surface of the Catoctin had a relief of 500–800 feet. Geologic maps of the South Mountains of Pennsylvania and Maryland by Stose and Bascom (1929) and Stose and Stose (1946) suggest the pre-Loudoun surface was more nearly peneplaned than it was considered to be by Keith in northern Virginia.

It is not clear that the erosional features associated with the boundary between the Catoctin volcanics and the Cambrian sediments were related to diastrophic movements of more than local significance, or that the erosional hiatus was long continued. Nevertheless, in the South Mountains of central Maryland and south-central Pennsylvania the Lower Cambrian sediments were deposited during a period that definitely succeeded the end of a period of vulcanism; except for thin tuffaceous slates of the initial Loudoun formation, the extrusive activity

of Catoctin time ceased abruptly and completely in the South Mountain area at the beginning of Lower Cambrian sedimentation. It may well be true, however, that in eastern Frederick County, east of the South Mountains, Catoctin vulcanism persisted longer and that the interbedded volcanics and sediments there classed as Glenarm represent an intergradational, earliest Cambrian stage not represented in the South Mountains.

A marked peculiarity about the relationships of the Catoctin metavolcanics is the lack of recognized basaltic material in the detritals of the Lower Cambrian Loudoun formation. Material from the rhyolitic flows occurs in abundance in some Loudoun strata in the Fairfield region (Stose and Bascom, 1929); the detrital fragments range to an inch and more in diameter in some conglomeratic layers, and finer-textured rhyolitic débris is recognizable in various slaty members. In Maryland, some of the sandy deposits of the Loudoun contain considerable feldspar along with blue quartz such as that characterizing granitic rocks of the supposed pre-Catoctin basement.

The rhyolitic materials of the Loudoun suggest that there was during Loudoun time much relatively local erosion from rhyolitic eminences of moderate elevation. Lack of observed basaltic materials is surprising in terms of the abundance of resistant metabasalt float to-day covering surfaces in the South Mountain area. Such lack might be attributed to several possible causes, such as, first, the possibility that the later extrusions were rhyolitic, and it was these rocks that formed the prominences of the Catoctin surface as Loudoun deposition was initiated. Second, under the conditions of weathering during Loudoun time, the basaltic flows, not then metamorphosed, may have decomposed to clays scarcely recognizable in the Loudoun deposits as they are examined to-day, whereas the rhyolites provided fresher, characteristic fragments. Third, the volcanic detritus included in the Loudoun deposits may largely have come from outside the area of the Catoctin exposures of the South Mountains, and if so may have been derived from uparched rhyolitic volcanics. Answers to these alternative hypotheses remain speculative at present.

The exposed pre-Cambrian rocks of the South Mountains differ markedly from the pre-Cambrian complexes of the Honeybrook Upland and Reading Prong in eastern Pennsylvania, as well as from the pre-Cambrian of the Adirondacks Mountains of New York. No volcanic sequence of Catoctin type is found in the latter areas. The pre-Catoctin plutonic complex exposed in the South Mountains is simpler than the pre-Cambrian basements known in the other areas, though its buried extensions may be equally complex.

GLENARM PROBLEM

Pre-Cambrian age of the Grenville metamorphics and their intruded plutonics in the Adirondacks is well established by their position with respect to the major unconformity below Cambrian strata, even though these contain no known faunas older than those of the Late Cambrian. Similar evidence, with position below

proved Lower Cambrian formations, assures the pre-Cambrian age of sedimentary gneisses and associated plutonics of the Reading Prong and Honeybrook Upland of eastern Pennsylvania. In the South Mountains of south-central Pennsylvania and central Maryland, Catoctin volcanics represent a large outpouring of lavas that ceased with beginning of deposition of an overlying 1-mile thickness of strata that contain Lower Cambrian faunas near their summit.

The Glenarm series, consisting of schists and some quartzites and marbles south and east of the Martic line in southeastern Pennsylvania and northeastern Maryland (Figs. 4, 5, 6), lacks such clear-cut relation with strata of paleontologically established Cambrian age. Hence, its own age, its structural condition, and its role in the stratigraphy and paleogeography of the early Paleozoics have been subjects of conflicting interpretations.

Modern studies of the Glenarm schists began near Philadelphia and Coatesville in southeastern Pennsylvania and near-by parts of Maryland. South of the Honeybrook Upland, Cambrian strata are succeeded in Chester Valley, Pennsylvania, by Conestoga limestone that in part, at least, is Beekmantown in age. The Conestoga in turn dips southward beneath albite-chlorite schists or phyllites of the South Valley Hills bordering the southern margin of Chester Valley. Areal geological features are illustrated in Figures 5 and 6.

Thirty to forty years ago, Bascom (1905–1909), Bliss and Jonas (1917), and others were in general agreement that the albite-chlorite schists of the South Valley Hills rest in sedimentary succession on the Conestoga limestone; hence, that they are Ordovician in age. The schists of these hills were named "Octoraro" by Bascom in 1909, with the comment that their contact with the Conestoga can not be a fault because of (1) the lithologic intergradation from the limestone to the schist; (2) widespread occurrence at the limestone-schist contact of a particular geodiferous bed; (3) essential parallelism of the limestone-schist contact with bedding of the limestone, even where secondary folds superimpose convolutions on the major structures.

Oligoclase-biotite schists south of the "Octoraro" belt near Philadelphia were at the same time termed Wissahickon schist by Bascom (1909), and were classed as pre-"Octoraro" and pre-Cambrian chiefly because of their more advanced metamorphism, and because they are intruded by plutonics unknown in the "Octoraro" of the South Valley Hills as well as in the Paleozoic limestones and quartzites of Chester Valley.

Near Doe Run (Fig. 5), Bliss (later Mrs. Knopf) and Jonas discovered "pre-Cambrian" Wissahickon above Setters quartzite and Cockeysville marble, and since the latter were identified with the Cambro-Ordovician quartzites and limestones of Chester Valley, it was concluded that the Wissahickon had been placed upon the Cockeysville by a major, fenstered overthrust.

The foregoing interpretations soon were greatly modified by Knopf and Jonas (1923, 1924). It was discovered that along the Peach Bottom syncline the Wissahickon plunges beneath the southern margin of the Peters Creek schist, and that

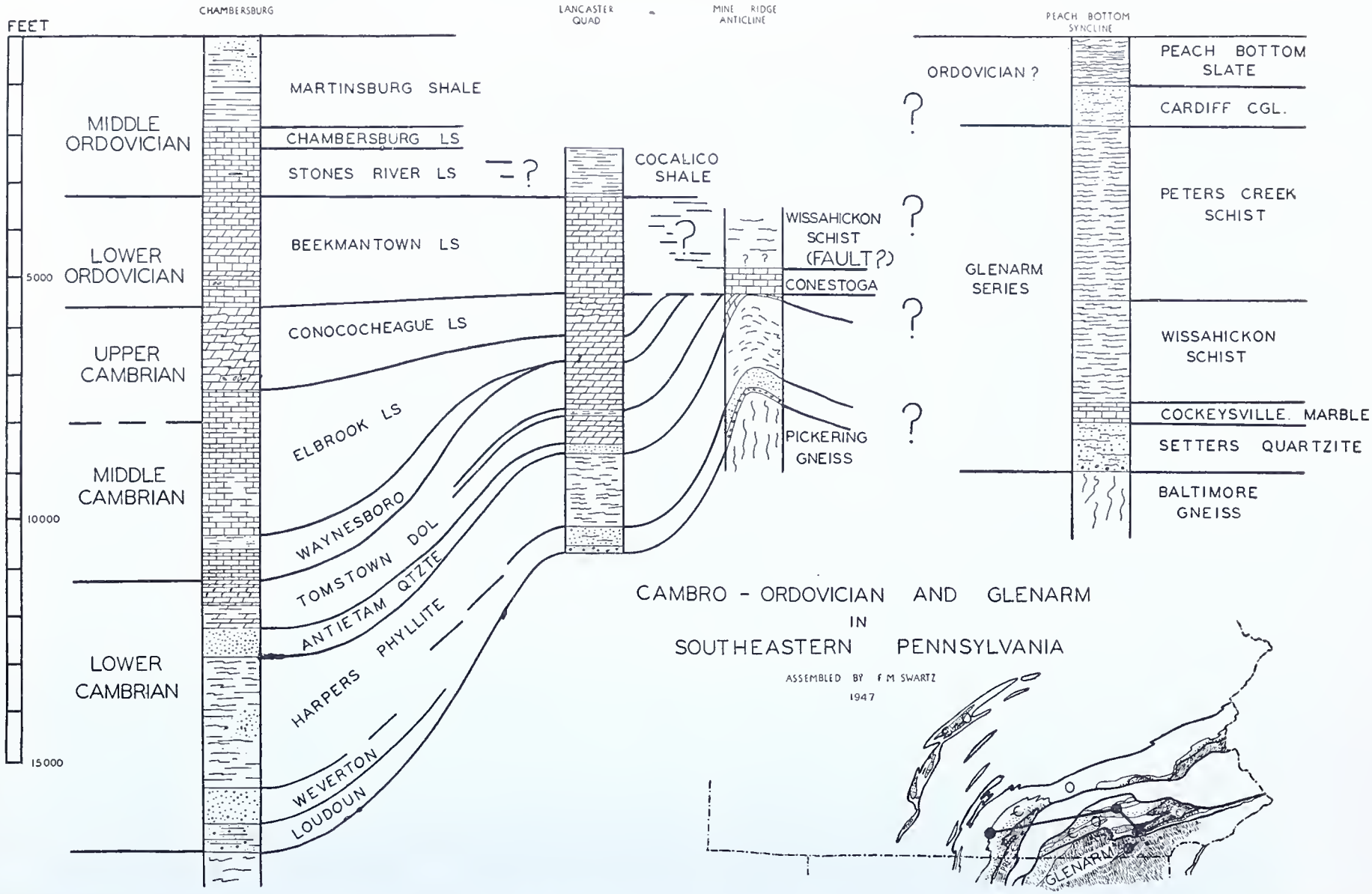


FIG. 6.—Stratigraphic chart comparing Cambro-Ordovician sequences near Chambersburg, Lancaster, and Mine Ridge, with Glenarm series of eastern part of Peach Bottom syncline.

it emerges on the northern side of the Peters Creek belt as the albite-chlorite type of schist that theretofore had been classed as "Octoraro." Knopf and Jonas hence concluded that the "Octoraro" is simply a less metamorphosed, northerly facies of the Wissahickon, and that the name "Octoraro" should be abandoned. Subsequent workers have agreed with this opinion, which may be accepted as a basic feature of the geology of the schists. Hawkins (1924), for example, placed emphasis on observable lateral intergradations near Doe Run and Avondale of the "Octoraro" and Wissahickon, and concluded that the southeasterly increase in metamorphic intensity resulted largely from increased soaking and feldspathization from acidic plutonics.

Knopf and Jonas (1923) furthermore suggested that near Doe Run and elsewhere the Wissahickon rests on the Cockeysville marble and Setters quartzite in normal sedimentary succession and not by the major fault that had been postulated in 1917.

These two generally accepted concepts of the schist structures were woven into a larger geologic pattern that has bred the vigorous controversy known as the Glenarm problem. The Wissahickon was grouped with the underlying Cockeysville and Setters formations, and overlying Peters Creek, Cardiff,[3] and Peach Bottom[3] formations, in the Glenarm series, named from a locality near Baltimore, Maryland. The Glenarm series *in toto* was classed as pre-Cambrian. This view of geologic age required postulation of a great overthrust to carry the albite-chlorite "Octoraro" facies of the Wissahickon onto the Ordovician limestones of Chester Valley; the assumed overthrust was termed Martic fault; its crop was drawn along the "Martic Line" of Figures 4 and 5; the fault subsequently was identified over a distance of several hundred miles in Pennsylvania, Maryland, and Virginia.

The crux of this structural interpretation turns upon the question of age of the Glenarm series. Assumption of pre-Cambrian age was advanced by Knopf and Jonas (1923, 1924) chiefly for the following reasons. First, the Wissahickon had "been shown to be" pre-Cambrian by Bascom in 1909 because of its intrusion near Philadelphia by gabbroic and granitic rocks that are "notably lacking" in recognized Paleozoics in adjacent areas, whereas gabbroic and granitic plutonics are found unconformably beneath Lower Cambrian strata in the Honeybrook Upland; second, according to work then in progress by Jonas, strata of probable Cambrian age occur unconformably on the Glenarm in Frederick and Carroll counties, Maryland, and in York County, Pennsylvania; third, Jonas' work in these counties further showed that the Glenarm bears volcanic intercalations closely similar to the pre-Cambrian Catoctin lavas of the South Mountains.

The views that the Glenarm rocks are pre-Cambrian, and that the Wissahickon was placed upon the Conestoga limestone of Chester Valley by a great over-

[3] In later discussion, the Cardiff conglomerate and Peach Bottom slate have been classed tentatively as Late Ordovician and removed from the Glenarm series because Maysville fossils are found in stratigraphically comparable Arvonia slate in Virginia.

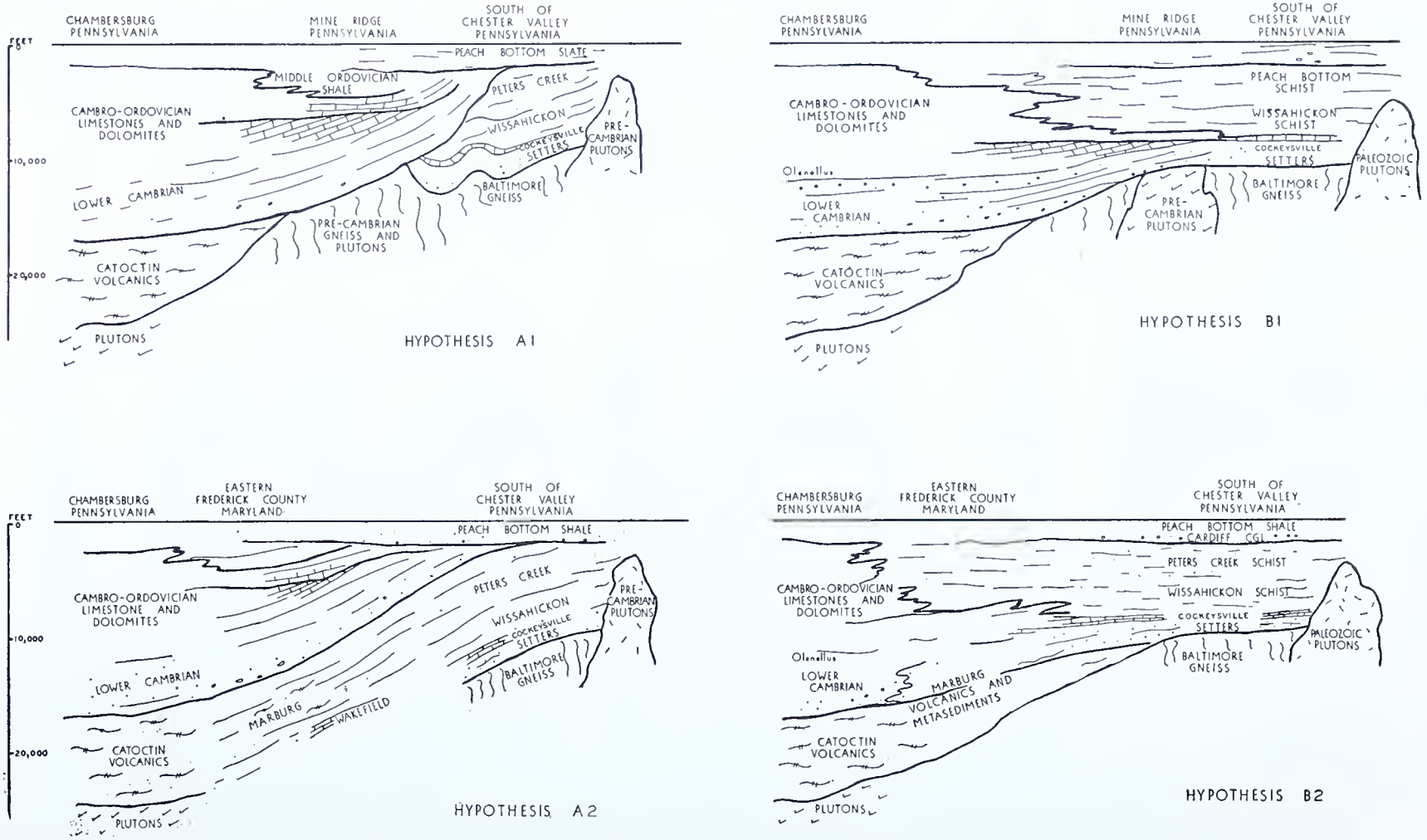


FIG. 7.—Diagrammatic sketches illustrating alternative hypotheses of Glenarm relationships. A1 and A2 are based on interpretation that typical Glenarm rocks, including Peters Creek, Wissahickon, Cockeysville, and Setters of area south of Chester Valley, are pre-Cambrian in age. B1 and B2 are constructed on alternative hypothesis that Glenarm rocks are a now-metamorphosed, more largely detrital, southeastern facies of Cambro-Ordovician of Chambersburg region. Relations of Marburg volcanics and metasediments of eastern Frederick County (A2 and B2) present special problems.

thrust, have been strongly opposed by Hawkins (1924), Malkin (1935), B. L. Miller (1935), and Cloos (1936, 1937, 1940). All of these men have favored the view that the Wissahickon of the South Valley Hills rests on the Conestoga limestone of Chester Valley with essential sedimentary conformity, and that the Martic Line is not here, at least, the line of a major belt of overthrusting.

In present review, it appears to the writer that there is much evidence favoring the opinion that the Glenarm series as developed south of Chester Valley is Cambro-Ordovician in age, and less reason for supposition of pre-Cambrian age.

Some of the alternative stratigraphic interpretations of Glenarm, Cambro-Ordovician relationships are illustrated graphically in Figure 7. Full consideration of these possible Glenarm relationships lies beyond the scope of the present discussion, and the following remarks deal with only a few of the significant problems.

Jonas has reported (Stose and Jonas, 1939; Stose and Stose, 1946) that the quartzites in Frederick and Carroll counties, Maryland, tentatively classed in 1924 as Lower Cambrian with the supposition that they rest unconformably on the Glenarm and give proof of its pre-Cambrian age, appear to belong in the Glenarm and can not satisfactorily be correlated with the Lower Cambrian quartzites of the South Mountains. Hence they are not, as was then believed, evidence of pre-Cambrian age of the Glenarm.

The original assumption of pre-Cambrian age of the Wissahickon schists rested primarily on their marked metamorphism, and their invasion near Philadelphia by plutonics that are not duplicated in the proved Paleozoics of Chester Valley, but instead are comparable with igneous bodies unconformably beneath the Lower Cambrian in the Honeybrook Upland.

With discovery that the Wissahickon changes northwestward into the albite-chlorite "Octoraro" facies of decreasing degree of metamorphism, the view that the strong metamorphism of the Wissahickon gives evidence of pre-Cambrian age began to lose force. Like the Cambro-Ordovician of Chester Valley, the more northerly part of the Wissahickon lacks intrusive plutonics, and indeed tends to be less metamorphosed than the proved Cambro-Ordovician sediments. Knopf and Jonas in 1923 called attention to the waning in metamorphic effects in the northerly Wissahickon rocks as compared with the Lower Cambrian strata of the Mine Ridge anticline, and thought this "one of the most puzzling problems of the region." It is not a puzzling problem if the Wissahickon rocks are Ordovician instead of pre-Cambrian in age.

The Glenarm succession in Pennsylvania south of Chester Valley resembles the recognized Cambro-Ordovician sequence of Mine Ridge and near-by Lancaster Valley as it begins with tourmaline-bearing quartzites, overlain by carbonate rocks and next by argillaceous deposits; furthermore, like the Cambro-Ordovician of Mine Ridge, it rests with major unconformity on an older gneiss complex. The thicknesses of these major members are significantly different in

the Glenarm as compared with the Cambro-Ordovician near Chambersburg and even near Lancaster, and the thickness changes have been cited as evidence of non-equivalence. It has not heretofore been properly emphasized that the thickness changes do no more than carry forward trends observed in the unquestionable Cambro-Ordovician sediments as they are traced from Chambersburg to the Lancaster Quadrangle and then to Mine Ridge and Chester Valley. (Fig. 6.) Whereas the supposition that the Glenarm is Cambro-Ordovician requires no more than a plausible type of facies change, such as might be expected in approach toward the source region of the Wissahickon clastics, the alternative view that the Glenarm is pre-Cambrian demands that there be a major change in rock sequence and in geologic history in the terranes immediately south and north of the Martic Line. There is no trace of a sedimentary series suggestive of the Glenarm beneath the Cambrian of the Honeybrook Upland. (Figs. 5, 6, 7.)

These lines of approach to the Glenarm problem, and other structural data as well, tend to support the opinion that the Glenarm metasediments south of Chester Valley are more probably Cambro-Ordovician than pre-Cambrian. It is desirable to recognize that the Glenarm as traced to some other regions, as in parts of Frederick and Carroll counties, Maryland, has been made to include rock groups not represented in the type Glenarm, and it does not necessarily follow that all so-called Glenarm rocks are Cambro-Ordovician even if this be true of the Glenarm south of Chester Valley. In particular, the extensive metavolcanics in eastern Frederick County pose special problems not readily resolved with present knowledge. Differing possible relationships of these volcanics are illustrated by diagrams in Figure 7.

Throughout discussion of the Glenarm problem, it must be recognized that these rocks occur under conditions of imperfect exposure, complexity of deformation, variation in intensity of deformation, original changes in lithologic characters, and lack of known fossils, so that interpretations are impeded. The valued studies of Bascom, Jonas, Stose, Knopf, and Cloos have all made major contributions to the eventual clarification of Glenarm relationships.

REGIONAL CHARACTERS OF PRE-CAMBRIAN BASEMENT AND POSSIBLE RELATIONS TO GRAVIMETRIC CONDITIONS AND APPALACHIAN DEFORMATION

Exposures of pre-Cambrian rocks in New York, Pennsylvania, and Maryland are too limited in area to allow more than preliminary guesses about regional relationships.

Present knowledge of the regional pre-Cambrian geology is summarized in Figure 8. On the northeast, in the Adirondack region, exposed parts of the pre-Cambrian consist of ancient carbonate, clay, and sand sediments that were intruded, sharded, and metamorphosed by successive basic and then more acidic plutons. Subsequently, but before initiation of Cambrian sedimentation, erosion carved this complex to a depth of thousands of feet and more probably several

miles, until the surface was reduced to a peneplane with relief ranging in some areas to possibly 300–400 feet.

Similar conditions occur southward in the Reading Prong and Honeybrook Upland of southeastern Pennsylvania, excepting that the early sediments were mostly sands and clays with few carbonates. Southeast of the Martic Line, the pre-Cambrian after exclusion of the Glenarm series consists of gneisses without certainly recognized pre-Cambrian plutons; the gneisses are thought to be metasediments.

In contrast with the geologic conditions in all of these areas, the Cambrian sediments of the South Mountains of south-central Pennsylvania and central Maryland are underlain by basaltic and acidic Catoctin lavas that, where fully developed, may be a mile or two in thickness. Just east of the South Mountains, the Catoctin series is questionably represented by volcanics of a narrow belt adjoining the Martic Line (Fig. 4). Southwestward, the Catoctin lavas extend for many miles along the Blue Ridge Province in Virginia.

Through most of the remaining four-fifths of the New York-Pennsylvania region, direct evidence about characters of the pre-Cambrian complex is lacking. A few wells drilled near the Adirondacks reached "granites," but do not greatly extend the known area of the Adirondack sequence. Several wells in western New York have also reportedly stopped in "granite," but these records are unsatisfactory because of inadequate description of the supposed pre-Cambrian material.

Significant tectonic relationships of the pre-Cambrian rocks are indicated by the known foliation features shown in very generalized fashion in Figure 8.

In the Adirondacks, the foliation planes have on the whole a dominant northeast-southwest trend. Some local variations in direction are related to the peripheries of stock-like intrusives.

The foliation in the Adirondack complex reflects pre-Cambrian and not post-Cambrian regional deformation and intrusion. Characters of the associated Cambrian and younger strata show clearly that there has been no appreciable modification of the foliation subsequent to the beginning of Potsdam sedimentation, and assumably not since some early stage in the period of erosion that culminated in the pre-Potsdam peneplanation.

The dominant foliation of the Adirondacks complex bears witness to the work, during pre-Cambrian time, of regional orogenic stresses aligned in substantially the direction that characterzied Appalachian mountain-making during a much later geologic period. The trend of the foliation furthermore is comparable with axial directions of Appalachian troughs of Paleozoic sedimentation. The geographic parallelism with pre-Cambrian foliation in the Adirondacks, and apparently also with pre-Cambrian foliation in terranes in Pennsylvania, Maryland, and New Jersey, suggests that the direction of Paleozoic trough-making and deformation was largely controlled by conditions established by pre-Cambrian, if not earlier, activities of the earth's crust.

Despite the parallelisms in direction of crustal failure, the pre-Cambrian and

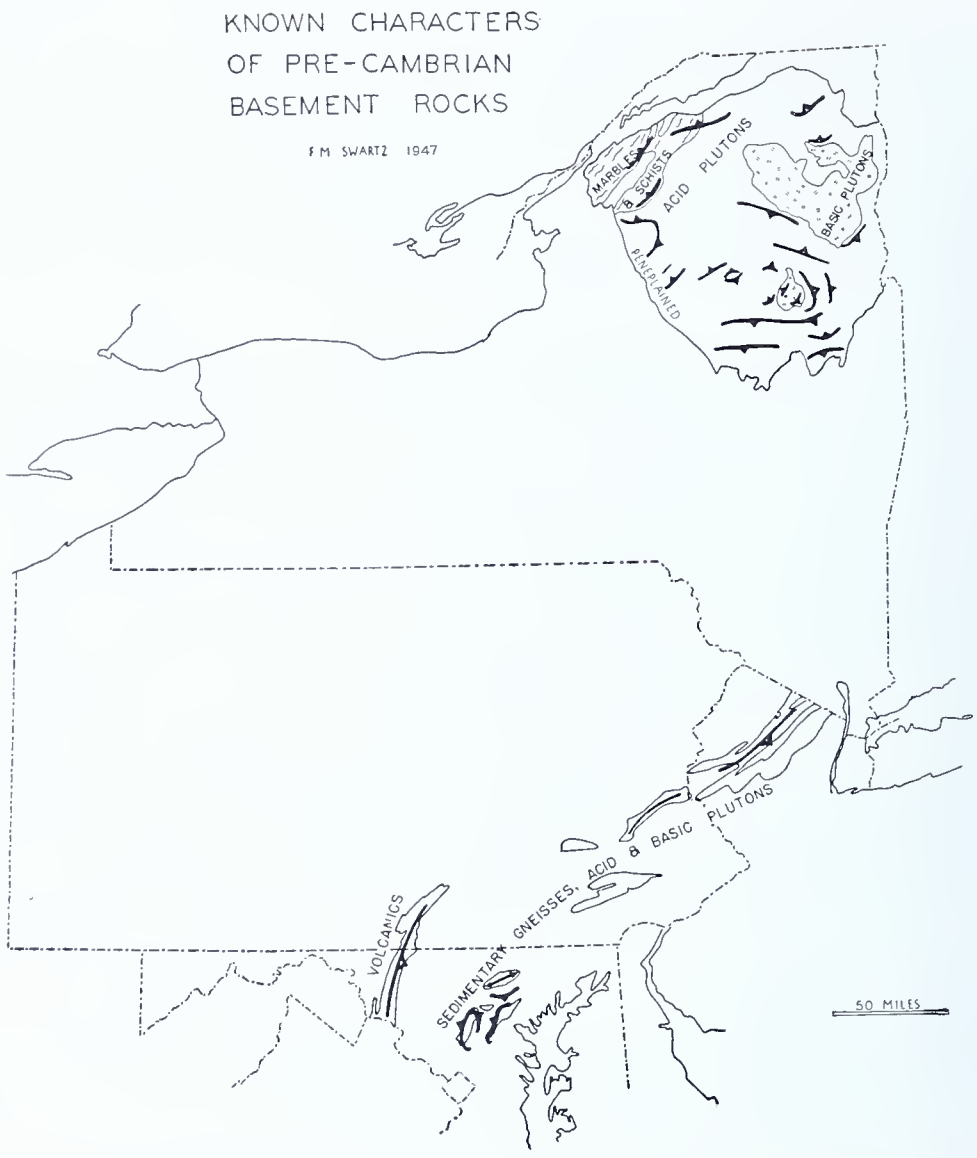


FIG. 8.—Generalized structural features of the pre-Cambrian basement in outcrop areas in Pennsylvania, Maryland, and New York. Foliation in Adirondack region simplified from Buddington (1939); in northern New Jersey from Franklin Furnace and Raritan folios of United States Geological Survey; in Baltimore gneiss domes of eastern Maryland from Broedel (1937); in volcanics of South Mountains from Cloos (1940). Adirondack structures are pre-Cambrian in origin; those of South Mountains are post-Cambrian; those of gneiss domes and of northern New Jersey are believed to be pre-Cambrian with post-Cambrian modifications.

Appalachian deformations were not co-extensive. In New York, and probably in Pennsylvania, areas of pre-Cambrian metamorphism reach far west of the belt of strong Appalachian disturbance, and affected relatively more inward parts of the continental platform.

The foliation shown in Figure 8 for pre-Cambrian terranes in Pennsylvania, Maryland, and New Jersey is in part post-Cambrian, in part pre-Cambrian modified in uncertain degree by post-Cambrian activity.

The southeastwardly dipping foliation of the Catoctin metavolcanics of the South Mountains of south-central Pennsylvania and central Maryland, likewise permeates overlying Lower Cambrian sediments. The foliation is post-Cambrian in age, and probably developed during Late Paleozoic Appalachian mountain-making. Strong regional pre-Cambrian deformation did not affect the Catoctin volcanics. Lavas and other rocks not foliated by pre-Cambrian orogenies may extend below the Paleozoics west and northwest of the South Mountains, above a floor of pre-Cambrian gneissic rocks.

The Baltimore gneiss of the gneiss domes of east-central Maryland was foliated previous to deposition of the overlying Glenarm metasediments of plausible Cambro-Ordovician age. Foliation of the gneiss was later modified to some degree by the orogeny that strongly deformed the Glenarm schists. The pre-Glenarm configuration of the foliation of the Baltimore gneiss is not fully understood; it is probable, however, that the original regional trend was nearly in accord with the later direction of the axes of the Appalachian folds. Locally, the foliation of the Glenarm schists and perhaps of the Baltimore gneiss is modified along the peripheries of plutons.

Little has been published about foliation directions of the pre-Cambrian rocks of the Honeybrook Upland and Reading Prong of eastern Pennsylvania, beyond the remark that there is a northeast-southwest trend in the latter area. In the Raritan and Franklin Furnace quadrangles in northern New Jersey, foliation of pre-Cambrian rocks is a pre-Cambrian structure that strikes lengthwise the grain of Appalachian deformation, and in general dips southeastward at high angles. The foliation may have been modified in dip by the Appalachian mountain-making, but its strike probably was not greatly altered.

Another type of evidence that bears on regional structure of the basement rocks of Pennsylvania is furnished by gravimetric data. Nettleton's (1941) map of isostatic anomalies in Pennsylvania, New Jersey, Maryland, and parts of the Virginias, is especially valuable (Fig. 9).

Nettleton gives evidence that the gravity anomaly curve of his Pittsburgh-Gettysburg traverse (bottom, Fig. 9) is strongly discordant with expected depths of the base of the Paleozoic sediments; hence, he concludes that the isostatic anomalies must reflect deeper conditions.

The gravimetric features illustrated in Nettleton's map furnish a basic pattern to which the regional structures of the "basement" rocks of the area must conform; "basement" rocks in this sense may include rock masses older than those that constitute the known pre-Cambrian of outcrop belts of the earth's surface, and also may embrace various deep, unsuspected post-Cambrian intrusive masses.

The dominant feature shown by Nettleton's map is a belt-like isostatic low that extends through west-central Maryland, central and eastern Pennsylvania, and southeastern New York. This low was termed "Blue Ridge" low by Nettleton. It has been renamed "Appalachian low" in Figure 9 since it dominates the Appalachian gravimetric pattern, and furthermore is not coincident with the

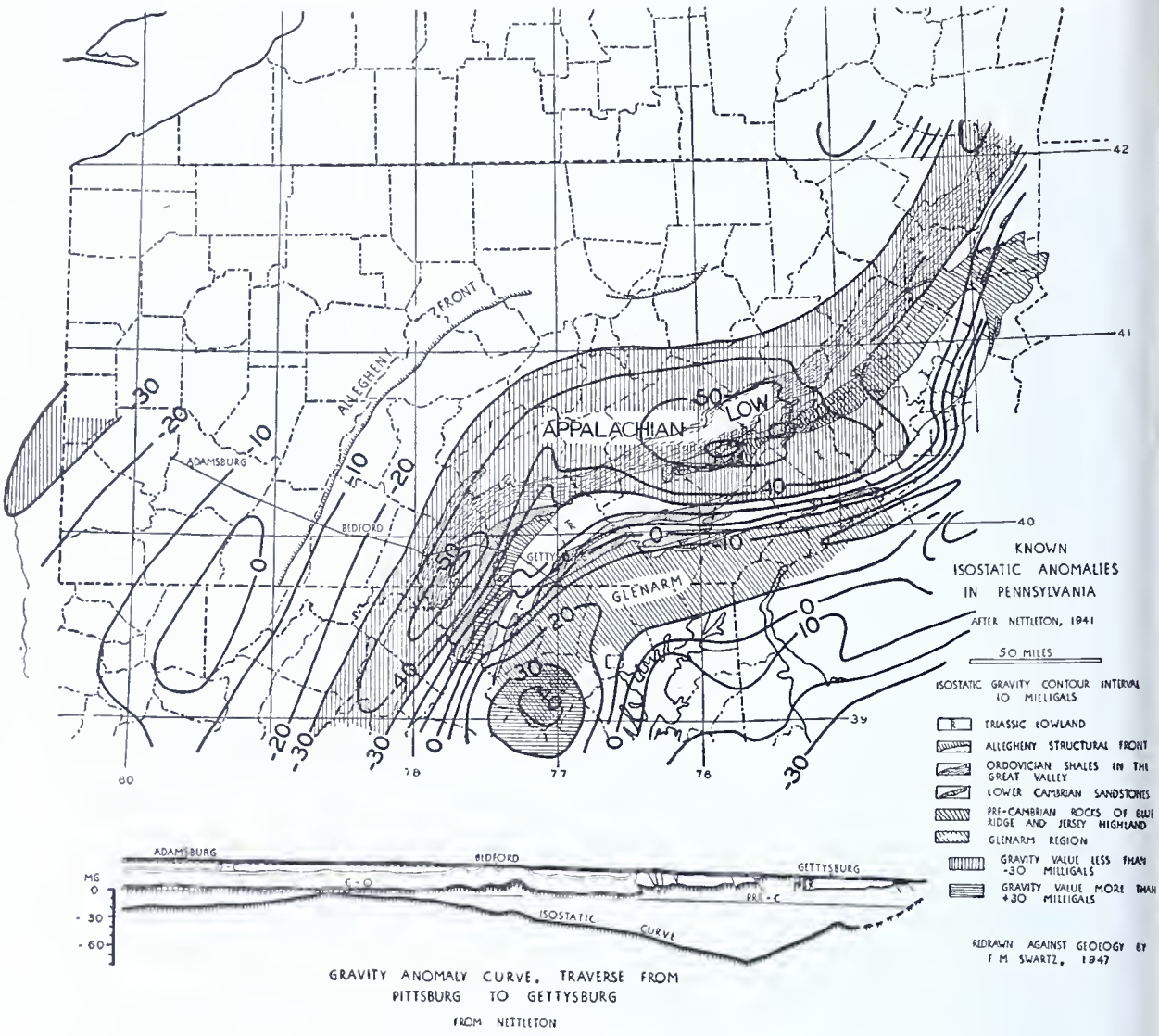


FIG. 9.—Known isostatic anomalies in Pennsylvania. Modified from Nettleton (1941).

Blue Ridge Province. In Virginia south of the map area of Figure 9, the major low parallels, but lies distinctly west of, the Blue Ridge Province. In central Pennsylvania, the axis of the low diverges markedly from the curving Blue Ridge belt, then swings eastward to the Reading Prong of the Jersey Highlands which are the northeast counterpart of the Blue Ridge. Farther north across Pennsylvania and New Jersey into New York, the axis of the low generally parallels the Jersey Highlands, but there also lies farther west.

Isostatically, the Appalachian low should mark the main root-system of the Appalachian Mountain belt.

During preparation of the present discussion, consideration was given to the possibility that the Appalachian low, especially where crossed by Nettleton's

traverse, might result from thick subsurface development of acidic phases of the Catoctin metavolcanics of the South Mountains. Several considerations make this supposition implausible. A very great development of the lavas would be required, and the widespread basaltic phases of the South Mountains area would have to be very subordinate. More importantly, the history of Appalachian sedimentation indicates that, during Paleozoic time, the region of the present-day low lay along the middle of a belt of widespread, gradual, long-continued, and

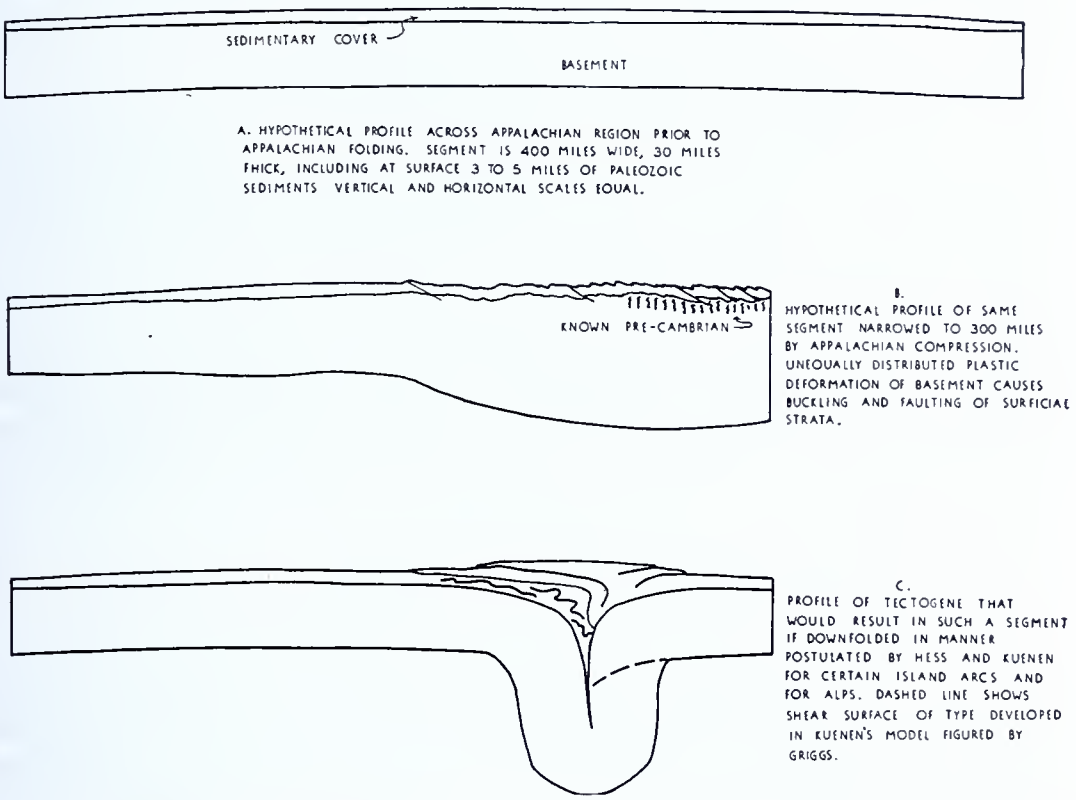

SEDIMENTARY COVER
BASEMENT
A. HYPOTHETICAL PROFILE ACROSS APPALACHIAN REGION PRIOR TO APPALACHIAN FOLDING. SEGMENT IS 400 MILES WIDE, 30 MILES FHICK, INCLUDING AT SURFACE 3 TO 5 MILES OF PALEOZOIC SEDIMENTS VERTICAL AND HORIZONTAL SCALES EQUAL.
KNOWN PRE-CAMBRIAN
B.
HYPOTHETICAL PROFILE OF SAME SEGMENT NARROWED TO 300 MILES BY APPALACHIAN COMPRESSION. UNEQUALLY DISTRIBUTED PLASTIC DEFORMATION OF BASEMENT CAUSES BUCKLING AND FAULTING OF SURFICIAL STRATA.
C.
PROFILE OF TECTOGENE THAT WOULD RESULT IN SUCH A SEGMENT IF DOWNFOLDED IN MANNER POSTULATED BY HESS AND KUENEN FOR CERTAIN ISLAND ARCS AND FOR ALPS. DASHED LINE SHOWS SHEAR SURFACE OF TYPE DEVELOPED IN KUENEN'S MODEL FIGURED BY GRIGGS.

FIG. 10.—Hypothesis of plastic deformation of Appalachian basement in relation to isostatic anomalies and to manner of deformation of Paleozoic sediments.

progressive subsidence. If control of the subsidence was isostatic, the belt should have been an isostatic high rather than low during the Paleozoic era, and in that case the present isostatic deficiency must have resulted from Late Paleozoic or subsequent crustal activity, not from pre-Cambrian events. It appears true that the present-day deep trenches of the western Pacific (Hess, 1948) are subsiding isostatic lows; however, these deep-water structures do not appear to the writer to be analogous with the Paleozoic Appalachian trough with its flood of shallow-water marine sediments and interlayered continental deposits, interrupted at many levels by surfaces of unconformity.

The present-day Appalachian low and other features of the Appalachian region of Pennsylvania can plausibly be explained by crustal shortening and

thickening of the general type illustrated in Figure 10A, B. These sketches present the hypothesis that, at the time of Appalachian folding, shortening occurred in the deep basement by widely distributed failure, here termed plastic though it assumably involved metamorphic recrystallization.

Figure 10B has been drawn to simulate the Appalachian region in Pennsylvania. Horizontal and vertical scales are equal. The basement shown in the diagram may have been complex in composition and in temperature; hence, in strength. The 30-mile depth used for the basement is no more than an approximation. Only the upper part of the basement as drawn in the sketches can be identified with pre-Cambrian rocks known at the outcrop.

The present discussion is not intended to cover the question of factors, such as distribution of stress, composition, moisture content, and temperature, that may have controlled the distribution of failure. In order to maintain analogy with the Appalachians, most of the shortening from 400 miles in 10A to 300 miles in 10B is allocated to the eastern half of the sketch. Thickening of the basement to compensate for the pervasive plastic shortening is drawn to scale. From place to place the sedimentary cover had to adapt itself to the distributed shortening within the basement; hence, buckling and faulting of the sediments are spread over a wide area, and there is no narrow axial region of abrupt net shortening of the surface of the basement such as is illustrated in Figure 10C. Minor plastic shortening on the west is reflected by small-amplitude flexures in the sedimentary cover.

The pervasive plastic shortening in 10B is favored by low effective strength, and contrasts with the more competent tectogene-type downfolding shown in 10C.

In 10B, it is not intended that the boundary between basement and sedimentary cover is a level of abrupt change in method of failure by rock flowage as compared with buckling and faulting. Instead, the change in mechanism of failure should be transitional from deep levels where flowage is predominant, to shallower levels where such failure is more and more replaced by folding and faulting.

Distribution of shortening throughout large rock masses is a well known geologic phenomenon. Quantitative data are wanting, but the foliation that pervades regional schists and gneisses may in many places represent reductions of half or more in the dimension perpendicular to foliation. Terranes to-day exposed to geologic observation show that regional metamorphism has been significant as a means of rock flowage at depths corresponding with the lower part of the sedimentary cover and higher part of the basement of Figure 10. Failure by rock flowage is plausible throughout the deeply covered basement if compressive stresses reach sufficient strength and perhaps especially if basement strengths are lowered by rises in temperature.

The tectogene hypothesis illustrated in Figure 10C has recently received favorable attention (Vening Meinesz, 1934; Kuenen, 1936; Hess, 1938, 1948; Griggs, 1941).

Judged from their form and their coincidence with isostatic lows, the western Pacific tectogene-trenches, finely illustrated by Hess (1948), may involve large scale downfolding due to tangential stress. Deepening of earthquake foci west of the trenches suggests some major type of overthrusting from the west, underthrusting from the east. It does not in any event follow that the trenches are in process of the extreme infolding shown in Figure 10C; floors of the present trench form comparatively gentle down-curves when drawn in transverse section. Distributed "plastic" rock flowage may be important at depth below the trench surfaces, especially in more advanced stages of their deformation.

Care must be used in any attempt to draw analogies between the western Pacific tectogene-trenches and Appalachian trough-sedimentation and folding. The trenches are a deep-sea phenomenon, external to the continental platform, situated along oceanic margins of the island arcs. During the Paleozoic history of the Appalachian region, the easterly lands that supplied vast quantities of detritus to the Appalachian trough may have resembled an island arc in general pattern. If so, they were very large during the periods of rapid sedimentary supply. Tectogene-trenches would be expected on their eastern, oceanic margins, not in the Appalachian region. The Paleozoic sediments of the Appalachian region suggest shallow seas spreading on a broad platform fluctuating about at sea-level, not the deep waters of the Pacific trenches.

Lower Cambrian

lower cambrian in vermont

Recognition of Lower Cambrian strata in North America resulted from a curious sequence of geological discoveries.

The Upper Cambrian Potsdam sandstone, where it flanks the pre-Cambrian along the Lake Champlain margin of the Adirondacks, dips eastward into Vermont at a moderate angle beneath strata of Beekmantown, Chazy, and Trenton age, and the Trenton rocks in turn disappear below more deformed carbonate rocks, quartzites, and slates. The slaty rocks near Georgia, Vermont, were classed as Hudson River shale with the view that they are post-Trenton in age, by astute James Hall in 1858 when he described from them, under the name *Olenus thompsoni*, a well preserved trilobite discovered by the Reverend Zachary Thompson.

Thompsoni was subsequently made the genotype of *Olenellus*, and olenellid trilobites, it was discovered (Walcott, 1889), characterize formations in Nova Scotia and Pennsylvania well below sediments bearing faunas allied to that of the Potsdam sandstone of New York. Thus instead of having the first-supposed post-Trenton position, *thompsoni* and its olenellid relatives have been proved to be prime guides for recognition of Lower Cambrian sediments not only in Vermont, but along the whole course of the Appalachians and Rockies of North America, as well as in the British Isles, Scandinavia, and eastern Asia.

The Lower Cambrian deposits of western Vermont, as they have been made

known through the work of Walcott, Keith, and others (Cady, 1945), consist of dolomites, quartzites, and subordinate slates, totalling approximately 3,000 to possibly 5,000 feet in thickness near Burlington, Middlebury, and Brandon. The dolomites, many of them sandy, form a half to as much as two-thirds of the mass; most of the remainder consists of quartzites, of which some are white and quartzose, whereas others in the Monkton and adjacent formations of the upper part of the Lower Cambrian are reddish and are associated with thin layers and laminae of red shale. The basal Cheshire quartzite is white above, brownish, schistose, more argillaceous in its lower part; at Milton Village, E. C. Jacobs (1935) identified such rock as Brigham Hall graywacke. The slate and slaty dolomite formations of the Lower Cambrian of Vermont are best developed near the town of Georgia; but even here they are distinctly subordinate in the Lower Cambrian. Most of the slates near Georgia are Upper Cambrian in age.

According to Cady (1935), the Monkton quartzite of the upper part of the Lower Cambrian of western Vermont,

> thins northeastward, eastward, and southeastward from a center that must have been near the site of the present Adirondacks. The Parker slate and its apparent stratigraphic equivalents in the Oak Hill slice are found in about the same stratigraphic position as the Monkton, but thickening north and east of it, suggesting a source of material diametrically opposite to that of the Monkton.

The fossil faunas and, to some extent, the lithologic characters indicate that the bulk of the known Lower Cambrian sediments of Vermont were deposited under marine conditions.

LOWER CAMBRIAN IN NEW YORK

The horizon of the Lower Cambrian reaches the surface in New York in three distinct areas: namely, first, along the flanks of the Adirondacks; second, in the median to lower parts of the valley of the Hudson River; and third in the Taconic region of the more northerly part of the Hudson River Valley.

The Lower Cambrian relationships in each of these three areas are considered in turn.

LOWER CAMBRIAN RELATIONSHIPS ALONG FLANKS OF ADIRONDACKS

Where the surface of the pre-Cambrian complex intersects the present ground level along the flanks of the Adirondacks, it is overlain in general by sandstones generally classed as Potsdam formation, save where these thin out and disappear on the southwest.

Near Potsdam, at the northern margin of the Adirondacks, the thickness of the Potsdam formation is irregular, varying from approximately 100 to 300 feet. The lower part of the formation is composed of reddish feldspathic quartzites and conglomerates; higher beds are whitish vitreous, quartzitic.

The Potsdam thickens eastward, and along the northeastern margin of the Adirondacks, may attain 1,500 feet. Here the Potsdam contains in its upper third fossils indicative of Upper Cambrian age. Beneath the fossiliferous, somewhat

dolomitic quartzites and sandstones, the middle third, more or less, consists mostly of whitish, non-fossiliferous quartzitic sandstone, whereas the lowest beds tend to be reddish and feldspathic, with conglomeratic layers in which there are pebbles of quartz and quartzite, and more rarely of gneiss.

The Potsdam is primarily an Upper Cambrian formation, as is indicated by its known faunas and by its intimate-relationships to other Upper Cambrian deposits. Nevertheless, fossils have not been discovered in the lower thousand feet or so of the Potsdam along the northeastern margin of the Adirondacks, so that these strata can not be correlated by direct paleontological evidence. The marked difference of the basal reddish, feldspathic beds of the Potsdam in contrast to overlying, cleanly washed white quartz sandstone has been emphasized by several authors, and Chadwick (1919) has suggested that the whitish and reddish parts deserve separation as two distinct formations.

The relations of the lower reddish beds of the Potsdam of the northeastern Adirondack margin to the reddish Monkton quartzite of Vermont need further investigation (compare Cady, 1935). The Monkton thickens and reddens toward the Adirondacks, and forms the Red Sandrock Range just east of Lake Champlain. Southeast and east of the Red Sandrock Range, the Monkton quartzites pass laterally into sandy dolomites; northeast they pass into dolomites and slates (Cady, 1935). The Monkton in part at least is marine, and bears some marine fossils; its sands and reddish clays were brought in, it is reasonably certain, from the general area in the northeastern Adirondacks where the lower Potsdam is reddish; hence consideration must be given to the possibility that the lower Potsdam beds of that area may have been deposited as the nearer-source part of a phase of weathering and sedimentation represented in Vermont by the Monkton deposits.

In brief, Lower Cambrian sediments are absent and probably were not deposited in the Adirondack region, save possibly for the reddish sandstones at the base of the Potsdam along the northeastern margin; the Lower Cambrian age of even these sediments is speculative and unproved.

LOWER CAMBRIAN IN SOUTHERN PART OF HUDSON RIVER VALLEY

The *Olenellus* fauna of the Lower Cambrian has been discovered in the median to southern parts of the Hudson River Valley of New York in the Poughquag quartzite and Wappinger limestone, which are exposed in small areas of the Poughkeepsie, Newburgh, and West Point quadrangles (Gordon, 1911; Holzwasser, 1926; Berkey and Rice, 1921). The Poughquag quartzite is approximately 125 feet thick near Newburgh and is well cemented, resistant, whitish to yellowish. It is moderately feldspathic, but free from ferromagnesian minerals; there is some tourmaline, apatite, zircon. The Wappinger mass is a complex, that is much deformed and poorly exposed. Discovery of the *Olenellus* fauna in some beds of the Wappinger in the Poughkeepsie Quadrangle shows that those particular layers are Lower Cambrian in age, if it may be assumed that the specimens were

not carried in by reworking; but other parts of the Wappinger according to their faunas represent Potsdam, Beekmantown, and Trenton formations. The total thickness of the Wappinger sequence is believed to be of the order of 1000 feet; how much of this was deposited in Lower Cambrian time is not yet clear, though it was probably not more than a small fraction of the total mass.

LOWER CAMBRIAN OF TACONIC PLATE

South of Albany in the valley of the Hudson River there are extensive shales, that in the middle of the past century were classed *en masse* as Hudson River shale. These rocks have been proved to be a great complex, varying in age and also in their regions of deposition. Included in the shales are formations that contain the Lower Cambrian *Olenellus* faunas, whereas other parts bear fossils of Ordovician age.

The net result of stratigraphic and structural studies has been to show that there is present in the Taconic Range and near-by parts of the Hudson River Valley a plate left as a remnant of a great sheet overthrust from the east, the plate having been separated by erosion from its old root-mass. The sediments of this plate are thus exotic, and no longer lie in the area of their original deposition. From the viewpoint of paleogeography they belong in New England at some distance east of the New York border, and not in the Hudson Valley region.

The Lower Cambrian deposits of the Taconic plate include the following formations as given by Ruedemann (1930).

	Thickness (Feet)
Schodack shale and limestone, containing an *Olenellus* fauna	100–200
Troy shale, greenish and purplish, *Oldhamia, Hyolithes*	25–100
Diamond Rock quartzite	0– 40
Bomoseen grit, olive, weathering reddish	20– 50
Nassau shale, greenish, some reddish, and quartzite interbeds	100–800

The Lower Cambrian of the Taconic plate thus consists of shallow-water sands and clays with subordinate calcareous deposits in the upper part. The Schodack beds contain brachiopods and trilobites of the *Olenellus* fauna and are definitely marine. *Oldhamia* of parts of both the Schodack and Nassau is a fringed trail representing aquatic worms or possibly some type of aquatic arthropod. It is not certain that this fossil reflects a truly marine environment.

The term Schodack is now commonly extended downward to include the Troy shale, Diamond Rock quartzite, and Bomoseen grit as locally varying members. The quartzite layers of both the Schodack and Nassau were mostly deposited as rather cleanly washed, quartzose sands with minor content of plagioclase grains. The shaly parts vary from purplish to more or less reddish, but it is not certain that any of these represent a continental redbed facies comparable, for example, with the Catskill redbeds of the Devonian.

The shaly limestones of the Schodack include widespread brecciated layers. Some of these have been formed by post-depositional deformation, but in general

they seem to represent intraformational limestone conglomerates. Sparsely distributed sand grains of the limestones are largely composed of smoky quartz comparable with quartz found in rocks of the Green Mountains of New England, but not duplicated so far as known in the pre-Cambrian of the Adirondacks.

The basement rocks upon which the Schodack and Nassau accumulated, remain unknown.

GENERAL DISTRIBUTION OF LOWER CAMBRIAN IN PENNSYLVANIA AND MARYLAND

Lower Cambrian sediments are thicker and more widespread in Pennsylvania and Maryland than in New York. They are exposed in three well defined areas, as follows (Figs. 4, 12).

1. South Mountains of south-central Pennsylvania and central Maryland
2. Quartzite hills and parts of adjacent valleys in area between Triassic Lowland and Martic Line
3. Quartzite hills and parts of adjacent valleys of Reading Prong

If the Glenarm series is Cambro-Ordovician in age, as seems probable to the writer (Fig. 7), then the Setters exposures southeast of the Martic Line belong to a fourth belt, in which parts of the Cockeysville and Marburg formations likewise may be Lower Cambrian.

The Lower Cambrian strata of each of these areas are in turn briefly considered, after which attention is given to the general sedimentation and paleogeography of the Lower Cambrian of Pennsylvania and New York.

LOWER CAMBRIAN OF SOUTH MOUNTAINS

The Lower Cambrian sediments attain reported thicknesses of approximately 1 mile in the South Mountains region of south-central Pennsylvania and central Maryland. Subordinate dolomites and limestones form the upper fifth or slightly more of the sequence, but the bulk of the mass is composed of ancient sands and clays now changed to quartzites and phyllites. The great volume of the clastic material is evidence of deep erosion of the adjacent source area.

As described by Stose (1909), Bassler (1910), Stose and Bascom (1929), and Stose and Stose (1946), the Lower Cambrian of the South Mountains is constituted as follows (thicknesses are in feet).

Carbonates: 1000–1200 feet
- Tomstown dolomite (Waynesboro formation, Fig. 15, placed at top of Lower Cambrian by some authors)

Terrigenous clastics: 4000
- Antietam quartzite, 500–1000
- Harpers phyllite, 1500–2500, including Mont Alto quartzite member, 0–1000
- Weverton quartzite, 1000
- Loudoun formation, 0–500

The *Olenellus* fauna distinctive of the Lower Cambrian occurs in the Tomstown and uppermost Antietam formation. Underlying strata have furnished no fossils save worm tubes of little value for correlation. The Waynesboro formation,

which overlies the Tomstown dolomite in the South Mountains region, is referred to the Lower Cambrian by some writers, because it seems to be continuous with part of the Rome formation of Virginia. Faunas satisfactory for correlation have not been found in the Waynesboro type deposits in Maryland and Pennsylvania.

The whole Lower Cambrian succession of the South Mountains has suffered low-grade metamorphism, so that original clayey sediments are now fine-grained phyllites, and clayey constituents of the quartzites tend to impart a less striking schistose structure.

The deformation, metamorphism, and incomplete exposure of the Lower Cambrian strata in southeastern Pennsylvania, all impede satisfactory measurements of thicknesses, and the cited values are at best only to be used as approximations. Cloos (1943) has shown that near the South Mountains some oölitic limestones have had their dimensions reduced by 50 per cent in one direction, increased by 100 per cent in another. Schistose structures likewise denote marked changes in dimensions, with maximum thickening in some direction along the plane of schistosity. It is difficult to make satisfactory allowances for these changes in dimensions. Imperfections of exposure and uncertainties about details of structure are still more troublesome, and have helped to restrict measurements to a relatively few localities. The terrigenous clastics of the South Mountains begin with the Loudoun formation, originally deposited as gravels, sands, and clays of which significant parts came from the rhyolites of the subjacent Catoctin series or at least from closely similar rhyolitic flows. In some areas, parts of the Loudoun are arkosic, with a mineral composition like that of the granitic and granodioritic plutons associated with the Catoctin. Detritus from the basaltic phases of the Catoctin has not been recognized in the Loudoun.

The Weverton quartzite, Harpers phyllite, and Antietam quartzite, overlying the Loudoun, are widely distributed and well bedded. Thc Weverton quartzite consists of well washed quartz sand, now cemented by silica overgrowths. There are some lenses of fine conglomerate. The Harpers typically is a clayey to somewhat silty clay deposit, its minerals now modified by metamorphism. As the Harpers formation is traced northeastward from Harpers Ferry at the junction of Maryland with Virginia and West Virginia, thin sandstones appear below the middle of the formation, and thicken to form the Mont Alto quartzite member which at some places forms most of the lower half of the Harpers formation. Like the Weverton, the Monto Alto quartzite consists in general of cleanly washed quartz sand, cemented by silica overgrowths. At some places the Weverton and Mont Alto are traversed by veins of milky quartz ranging upward to several feet in thickness. These evidently were formed during the Appalachian mountain making and may well have resulted from the same silica-charged solutions that produced the silica overgrowths of the quartz grains.

At its top, the Harpers formation becomes sandy and passes into the Antietam quartzite. East of Fairfield, at least, the lower part of the Antietam is decidedly graywackyish, and contains thin interlayers of pure quartz sandrock interspersed

with thicker layers of grayish impure sandstone. Parts of the non-quartz materials of the rock form irregular, discontinuous laminae extended along the direction of schistosity. Higher parts of the Antietam contain more of the purer quartz sand layers, until at the summit there are dolomitic sandstones that are sparingly fossiliferous, and that are transitional with the overlying Tomstown dolomite.

The Tomstown formation, at the top of the Lower Cambrian chiefly on the western flank of the South Mountains, is composed of limestones and dolomites, with some shaly material below the middle of the mass. It is overlain by the sandy clays, silts, and impure limestones of the Waynesboro formation.

LOWER CAMBRIAN OF AREA BETWEEN TRIASSIC LOWLAND AND MARTIC LINE

In the area between the Triassic Lowland and the Martic Line, the Lower Cambrian sediments are as measured everywhere thinner than in the South Mountains area. In general, however, there is an upper carbonate series, a lower clastic series, and the clastic series includes median Harpers clayey rocks now changed to phyllites. The reported sequences can be summarized as follows (thicknesses are in feet).

	York County		*Lancaster County*		*Chester County*
	Pigeon Hills	*Thomas-ville*	*Near Lancaster*	*Mine Ridge*	*Southwest of Phoenixville*
Upper carbonates:					
Ledger dolomite, Kinzers shale and limestone, Vintage dolomite	2,000	2.000	1,700	200–0	800
Lower clastics:					
Antietam quartzite, Harpers phyllite, Chickies quartzite with Hellam conglomerate member	2000–2,500	2,000	1,900	1,800	1,000–1,200

The Hellam conglomerate is composed of conglomeratic quartzites and phyllitic quartzites and puddingstones. In York County where it reaches as much as 500 feet in thickness, there are numerous layers bearing well rounded 2–3-inch pebbles and some 6-inch cobbles of milky quartz and quartzites, with a few pebbles of jasper. Rhyolitic fragments such as occur in the Loudoun have not been noted.

The Chickies quartzite is in general a moderately pure quartz rock, but contains some phyllites and slates. Scolithus tubes occur in some beds. The Antietam quartzite becomes phyllitic toward the east, where it is not readily differentiated from the Harpers formation.

All of the formations are increasingly affected by metamorphism in the more easterly sections. Along the flanks of Mine Ridge in Lancaster County, the Harpers formation is described by Knopf and Jonas (1923) as an albite-chlorite schist, with incipient development of biotite, and with the albite recrystallized so that its intergrowths produce spongiform individuals bearing inclusions of the other constituents of the rock. Hellam conglomerate beds of the Chickies contain crushed pebbes of granulated quartz and glassy blue quartz in a magnetite-rich, mica schist matrix.

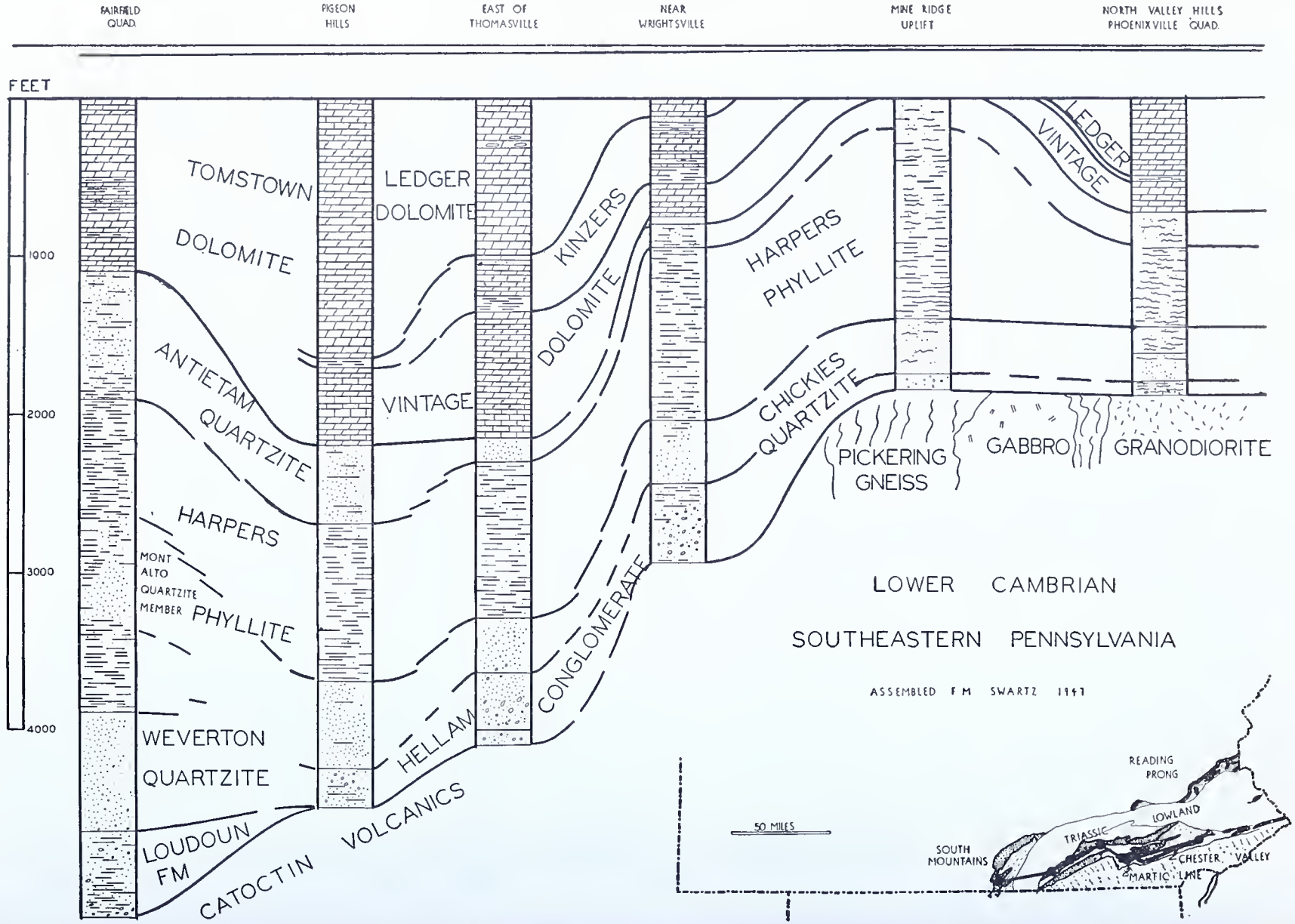


FIG. 11.—Stratigraphy of Lower Cambrian in south-central and southeastern Pennsylvania.

East of the South Mountains, the Tomstown-age dolomites first thicken to more than 2000 feet, then thin and along part of the Mine Ridge uplift wholly disappear (Fig. 11). Farther east, in the southern part of the Phoenixville Quadrangle, the dolomites again are present.

Through most of the area, the shaly Kinzers formation separates the overlying Ledger dolomite from the underlying Vintage dolomite. The Kinzers formation contains fairly numerous fragments of *Olenellus* and other distinctive Lower Cambrian fossils. Trilobites are rarer in the Vintage and Ledger, which contain some *Cryptozoön*-rich beds.

LOWER CAMBRIAN OF READING PRONG

The Lower Cambrian sequences of the Reading Prong area in Berks, Lehigh, and Northumberland counties, eastern Pennsylvania, are not illustrated in accompanying stratigraphic charts. They are essentially as follows (thicknesses are given in feet).

	Lehigh County	*Northumberland County*
Upper carbonates:		
Tomstown limestone, dolomitic and somewhat argillaceous	1,000±	1,000±
Lower clastics:		
Hardyston quartzite, some conglomerates, cherts, and arkoses	0–250	25–350

ASSUMED LOWER CAMBRIAN OF GLENARM BELT

If the Glenarm series is Cambro-Ordovician in the fashion here favored (Fig. 7B), then the Setters quartzite should be Lower Cambrian in age. Part of the overlying Cockeysville marble may also be Lower Cambrian, but judged by analogies with the Paleozoics of Chester Valley, much of the Cockeysville may be Late Cambrian or Early Ordovician.

The Setters quartzite is approximately 1,000 feet thick in the Doe Run region of southeastern Pennsylvania, and with local variations maintains this general thickness southward toward Baltimore. Parts of the Setters are vitreous, formed from cleanly washed quartz sand; parts are phyllitic and represent clayey or possibly graywackyish sand deposits. As is true of the Chickies formation of the hills bordering Chester Valley, some beds of the Setters quartzite contain needles of black tourmaline in moderate numbers.

REGIONAL RELATIONS, SEDIMENTATION, AND PALEOGEOGRAPHY OF LOWER CAMBRIAN IN PENNSYLVANIA, MARYLAND, AND NEW YORK

The characters and geographic variations of Lower Cambrian strata in the various outcrops in Pennsylvania, Maryland, and New York, briefly summarized on foregoing pages and in part illustrated in the stratigraphic chart of Figure 11, furnish data used for synthesis of the preliminary isopachous map of Figure 12, and for the interpretive stratigraphic chart and paleogeographic map of Figure 13.

None of these interpretive maps and charts can be considered fully established.

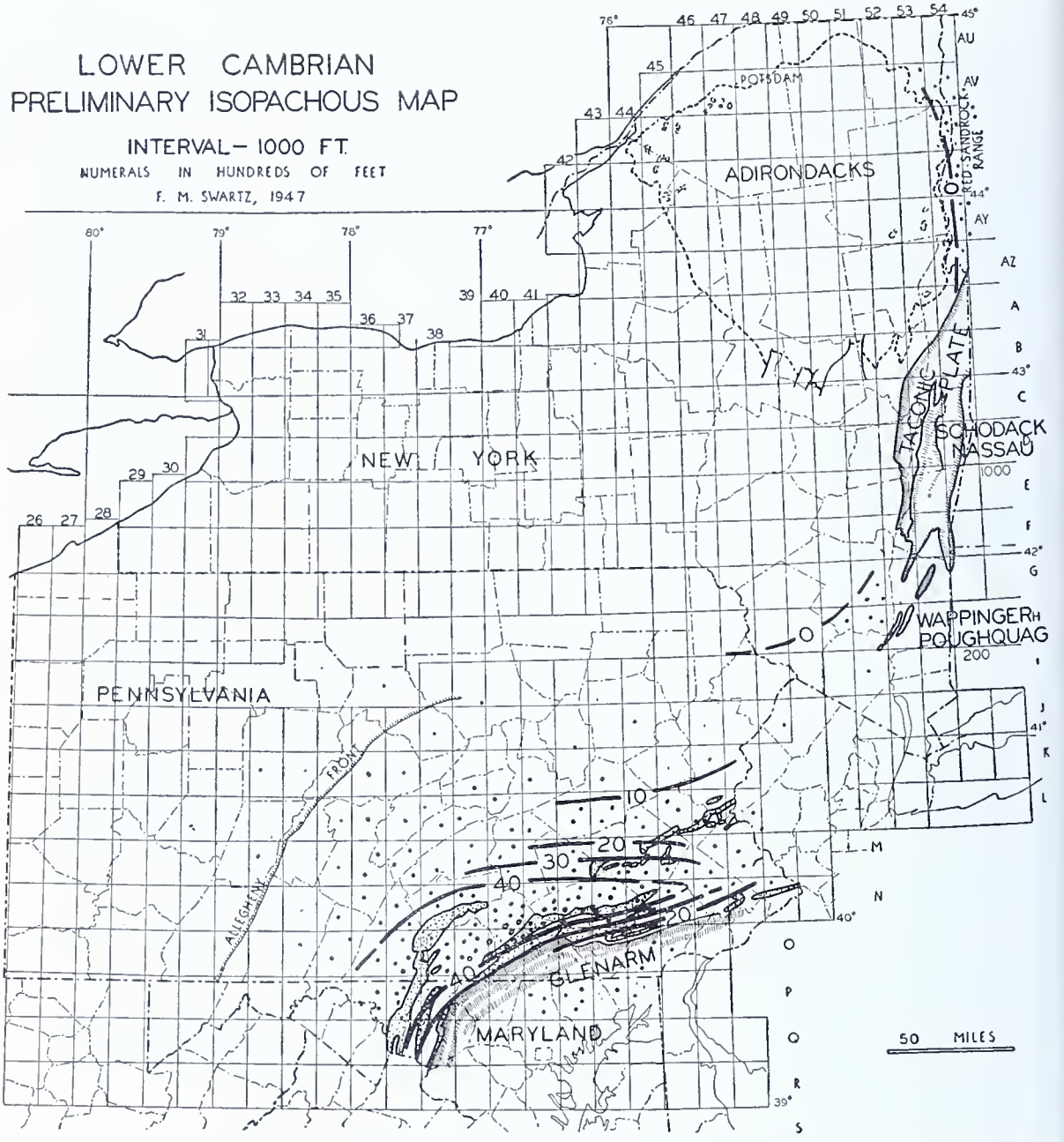
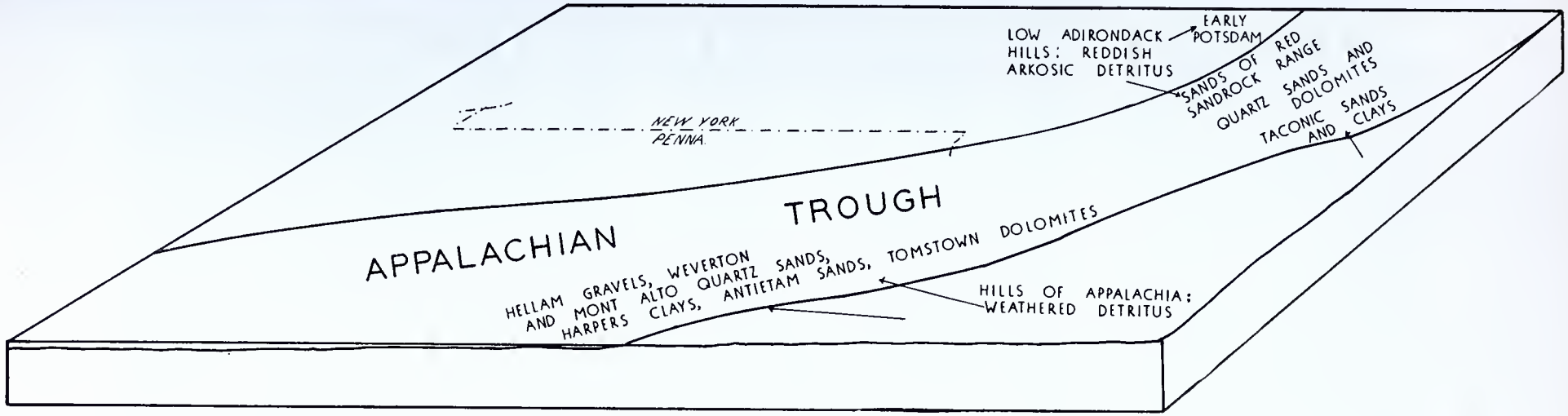


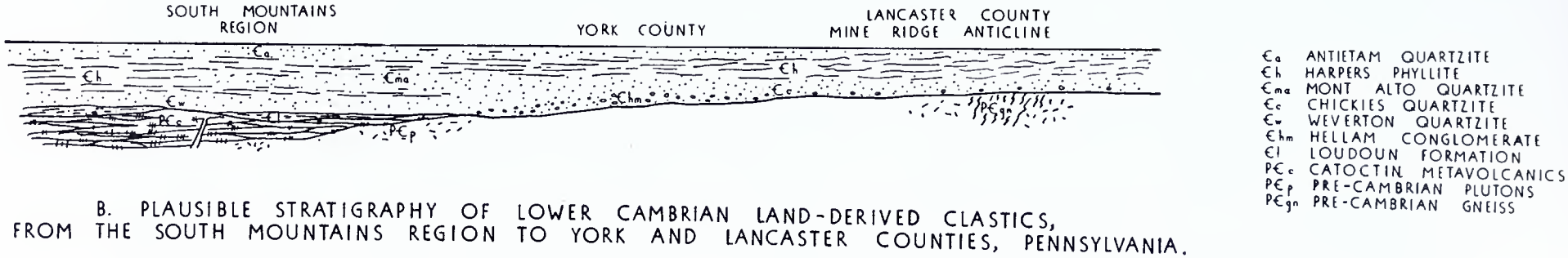
FIG. 12.—Preliminary isopachous map for Lower Cambrian in New York, Pennsylvania, and Maryland.

They express relations that seem plausible at the present stage of knowledge, but that must be subjected to further scrutiny from continued studies of regional stratigraphy and sedimentation.

Despite uncertainties about various special problems, it is reasonably clear that the Lower Cambrian sediments of Pennsylvania, Maryland, and New York


LOW ADIRONDACK HILLS: REDDISH ARKOSIC DETRITUS
EARLY POTSDAM SANDS OF SANDROCK
RED RANGE QUARTZ SANDS AND DOLOMITES
TACONIC SANDS AND CLAYS
NEW YORK
PENNA
APPALACHIAN TROUGH
HELLAM GRAVELS, WEVERTON AND MONT ALTO QUARTZ SANDS, HARPERS CLAYS, ANTIETAM SANDS, TOMSTOWN DOLOMITES
HILLS OF APPALACHIA: WEATHERED DETRITUS

A. PLAUSIBLE PALEOGEOGRAPHY OF LOWER CAMBRIAN SEDIMENTATION AND SOURCE AREAS OF LAND-DERIVED CLASTICS. ARROWS SHOW DIRECTIONS OF SEDIMENTARY TRANSPORT.



B. PLAUSIBLE STRATIGRAPHY OF LOWER CAMBRIAN LAND-DERIVED CLASTICS, FROM THE SOUTH MOUNTAINS REGION TO YORK AND LANCASTER COUNTIES, PENNSYLVANIA.

FIG. 13.—Plausible paleogeography of Lower Cambrian sedimentation in New York, Pennsylvania, and Maryland, with interpretive stratigraphic chart for Lower Cambrian terrigenous clastics of south-central and southeastern Pennsylvania.

were deposited in an elongate trough, trending northeast-southwest in about the manner shown in Figure 13, and that thicknesses have essentially the trends indicated in Figure 12. The axis of maximum thickness of sedimentation traverses central Maryland, crosses southeastern Pennsylvania, northern New Jersey, and southeastern New York, and extends into northwestern New England. Thicknesses change along the axial line, so that there is a marked reduction from central Maryland and south-central Pennsylvania toward southeastern New York.

The axis of maximum thickness of the sediments should not be interpreted as the axis of maximum depth of water. The two probably did not coincide at most times, and it is probable that the greatest thickness of sediments and of greatest downwarping lay toward the area of erosion.

Insofar as marginal parts of the sediments were non-marine, the margins of the trough of deposition and of the associated seaway were not coincident at any particular time. Such sediments as the Hellam conglomerate, in particular, may well have been the deposits of a delta plain rather than sea deposits.

Throughout the trough area, Lower Cambrian sedimentation in general began with sands, clays, and some gravels, representing a period during which neighboring lands were at best moderately elevated and were undergoing fairly rapid denudation. Some red-stained detritus accumulated in the Vermont area, and subordinate purplish and some reddish beds occur in the shales of the Taconic plate. Reddish sediments are rare or absent elsewhere.

In the later part of Lower Cambrian time, erosion was less active in the lands bordering the trough, and there was widespread accumulation of carbonate rocks that chiefly are dolomites. In the Vermont region, at least, dolomites deposited toward the median part of the trough interfinger toward the margins with clayey and sandy sediments deposited toward the marginal regions.

The geology of the Adirondacks and New England shows that there, during Lower Cambrian time, the western margin of the Appalachian depositional trough trended north and south and lay just east of the Adirondack area. Deposits formed near the median part of the trough are dominantly dolomites and reach maximum thicknesses of 3000 to possibly 5000 feet. Fossils of the *Olenellus* fauna occur at several horizons, and give evidence that the waters generally were marine. Sandy, in part sparingly feldspathic detritus was brought into the trough from hills of the Adirondack region on the west. Many of these sandy sediments are whitish to grayish, and commonly the sands are relatively quartzose excepting some local graywacke near the base. Some sands of the higher part of the Lower Cambrian of Vermont, however, are stained with reddish clay. These contribute chiefly to the Monkton formation that extends eastward from the Red Sandrock Range with decrease and final disappearance of thin reddish sand and silty tongues or stringers, and concomitant increase of the dolomite interbeds. Some of the lower reddish, feldspathic parts of the thick Potsdam beds of the northeastern flank of the Adirondacks may represent near-source, alluvial-lagoonal phases of the partly marine Monkton sediments.

In northern Vermont some slates occur in the Lower Cambrian. The manner in which they interfinger with the dolomitic facies indicates that the slate formations represent clays derived from the eastern rather than from the western margin of the depositional trough. Although reddish clays stain the Montkon sands, the detritus from the Adirondack hills is not known to have supplied the volume of clayey sediments that would be expected if it came from a thick soil cover being renewed by deep weathering. At the same time, the detrital sediments do not contain the abundance of feldspar that would be expected from simple mechanical erosion of the pre-Cambrian plutons that should have dominated the Early Cambrian erosional surface of the Adirondack region.

The 1000 feet or so of clayey and sandy Schodack and Nassau sediments of the Taconic plate near Albany, New York, were deposited many miles east of their present, overthrust location. Their structural relations, the presence in the upper calcareous beds of sand grains of smoky quartz similar to types known in pre-Cambrian rocks of New England but not of the Adirondacks, and perhaps the proportion of shale, suggest that these sediments were derived from lands east and not west of the depositional trough.

The upper, more calcareous part of the Lower Cambrian of the Taconic plate contains brachiopods and trilobites of the *Olenellus* fauna and definitely is marine. Lower beds contain the trail-fossil, *Oldhamia*, that may represent bottom-crawling worms or arthropods of shallow bodies of water, though these were not necessarily the normal marine waters of the open ocean of Lower Cambrian time. The Nassau and Schodack contain subordinate purplish and some reddish shales but even these as now known are not provably of continental type.

The calcareous beds of the Schodack include extensive intraformational limestone conglomerates, likely representing broken up and redeposited, mud-cracked lime-clays of tidal flats. In underlying parts of the sequence there are numerous alternating interbeds of shale or slate and quartzite. Detritus brought in from the easterly source area included well weathered sand and clay materials, that underwent sorting and separation in the basin of deposition by action of wave agitation and currents. The detritus may largely have come from weathering of pre-Cambrian sediments or metamorphosed sediments, though there is sufficient plagioclase to suggest that some of the parent rocks were igneous. Somewhat more clay than sand reached the area of Schodack and Nassau deposition, and persistent interbedding of the sands and clays shows that there was continuing, evidently mixed supply of the two phases of detritus.

Some of the quartzite beds are coarse-grained, and a few of them are finely conglomeratic. Pebbles more than a half-inch in diameter are, however, very rare.

Unlike the Nassau and Schodack of the Taconic plate, the Poughquag quartzite and basal, Lower Cambrian part of the overlying Wappinger limestone of the Hudson River Valley, were deposited in their present region of occurrence. These sediments are thin, and in view of their own characters as well as because of the

trend of the trough farther north, probably lie fairly close to the northwestern shore of the Early Cambrian trough. The neighboring zero line of the Lower Cambrian sediments has been located in Figure 12 on this basis.

In the Newburgh area, the Poughquag quartzite is 100–200 feet thick. Its sands are relatively clean and quartzose; they contain a small percentage of feldspar but ferromagnesian minerals are very rare.

The *Olenellus* fauna occurs in the basal part of the Wappinger limestone, and gives clear proof both of Lower Cambrian age and of marine environment. Higher parts of the Wappinger contain Upper Cambrian and Early to Middle Ordovician fossils.

In southeastern Pennsylvania, the Lower Cambrian sediments, and more especially the land-derived clays and sands, first thicken and then thin somewhat as they are traced from their more northerly to more southerly exposures. These changes provide the basis for outlining the isopachous trends sketched in Figure 12, and for establishing the direction of the axis of the Appalachian trough of downwarp and deposition. Along the axis, the clastic sediments thicken southwestward, reaching reported values of approximately 4000 feet in the South Mountains region of south-central Pennsylvania and central Maryland.

A considerable amount of information about the pattern of textural and facies changes has been accumulated in the past 35 years, and in part is illustrated in Figure 11 by means of comparisons of described local sections. The same changes are illustrated in more interpretive fashion in the lower part of Figure 13, and are involved in construction of the isopachous and paleogeographic maps of Figures 12 and 13, respectively. Geographically, gravels from the adjacent source lands reach greatest development in York County, as is illustrated by Figures 4 and 11, taken in combination. The line of the sections of Figure 12 and lower part of Figure 13, extends obliquely to the axis of the Appalachian trough, not directly across it. In considering the pattern of textural changes in relation to paleogeography and conditions of deposition, it is necessary to remember that the sediments are not believed to have been transported along the line of these charts. The western sections lie near the axis of the trough where maximum thicknesses were attained. More eastern sections are south of the axis of maximum thickness and so perhaps are closer to the southeastern margin of the basin of deposition. The sections from central York County to the more northern part of the South Mountains seem more nearly to represent the direction of sedimentary transport.

Giving first attention to the terrigenous clastics in southeastern Pennsylvania and central Maryland, one finds that clays and sands are subequal in volume in the areas of exposure, although clays may be predominant farther west where the Lower Cambrian sediments extend beneath younger strata.

Clayey parts of the Harpers of Maryland interfinger with the cleanly washed quartz sands of the Mont Alto quartzite of Pennsylvania, that is believed by Stose

and Jonas to grade farther east into the Chickies formation. Both the clayey and sandy formations preserve the good bedding of water-laid deposits, excepting where masked by easterly increase in metamorphism. The volume and proportions of clay and sand, and the manner of interfingering, suggest that separation of the two facies was largely accomplished in the basin of deposition by active sorting of clayey sands and sandy clays discharged by rivers draining the bordering source lands. Because the Weverton and Mont Alto sands are quartzose and cleanly washed, even though much of the Harpers clays are silty or arenaceous, it is plausible that the sand winnowing took place in shallow reaches of the seas, where wave agitation and current movements were effective in terms of rate of influx of detritus.

Although the bedding and extent of the Weverton-Harpers-Mont Alto sediments, and cleanliness of the quartz sand suggest accumulation in extensive bodies of water, the sediments have furnished no fossils of shelly marine animals. A significant possible factor in such lack of marine shells is freshening of waters where seas spread on continental surfaces are poorly connected with the open ocean, reducing tidal and current influx of marine waters in comparison with inflow from rivers. Under present conditions, fresh water reportedly extends during calm weather for some miles to sea off the the mouth of the Amazon, and a fresh-water "shadow" occurs along the western side of the Mississippi delta. Smaller rivers might have had much greater effect in the shallow Paleozoic waters of the Appalachian region, wherever connections with the open oceans were especially imperfect.

Like the Weverton and Mont Alto, much of the Chickies formation consists of vitreous quartzites that originated as cleanly washed, water-spread quartz sand. Some parts of the Chickies, however, were deposited as clays and clayey sands.

The Hellam conglomerate, which rests on the pre-Cambrian surface as the basal member of the Chickies formation in parts of York and Lancaster counties, contains pebbles and in some places 6-inch cobbles of milky quartz, quartzites, and jasper. Published photographs suggest that the pebbles and cobbles tend to be rounded rather than shingle-like. The matrix commonly is impure, phyllitic, originally clayey or graywackyish sand. It is plausible that many of these poorly cleansed, conglomerate and cobble deposits, along with some of the associated clayey and sandy sediments, accumulated in delta plains of streams flowing swiftly from neighboring uplands.

In the South Mountains region, the varying rhyolitic and granodioritic detritus of the basal Cambrian Loudoun sediments gives evidence of local erosion and deposition. It is probable that this was accomplished by streams working on the uneven surface of the Catoctin volcanics and associated, exposed granodioritic plutons.

Detailed correlations of the changing textural facies of the Lower Cambrian terrigenous clastics of southeastern and south-central Pennsylvania are not well

enough established to fully resolve questions about location of source lands and directions of sedimentary transport.

In the South Mountains in central Maryland and south-central Pennsylvania, the Mont Alto quartzite thickens northeastward, replacing an increasing proportion of the clayey sediments of the Harpers formation and giving some suggestion of a northerly land source. On the other hand, the Weverton-Mont Alto sands of the South Mountains of Franklin and Cumberland counties, Pennsylvania, are believed to pass eastward into the Chickies quartzite and Hellam conglomerate. The Hellam conglomerates reach their greatest thickness, and develop the coarsest gravel and cobble beds, in the middle part of York County, east of the South Mountains (for geography see Fig. 4), and this change suggests derivation from land areas southeast of the Appalachian trough. The gravel and cobble beds again become less conspicuous in the still more southeastern exposures; but in view of thinning of the Lower Cambrian detritals it is reasonable to suppose that here the base of the Lower Cambrian is transgressive, and the gravel beds are reduced by unconformity. On the other hand, the disappearance of the gravel beds from York County to the thick Lower Cambrian of the South Mountains seems to be by lateral gradation into finer-grained sediments that are equivalent in age.

The net result based on the relationships as now understood, seems to favor the view that the bulk of the Lower Cambrian gravels, sands, and clays in south-central and southeastern Pennsylvania came from source lands southeast of the Appalachian trough.[4] It furthermore appears that there was a path of major sedimentary transport directed toward the York, Cumberland, and Franklin County region, so that maximum thickness of sediment and coarsest cobbles were carried into that area. Lesser volumes of the detritals reached the trough in the more easterly part of Pennsylvania (compare Fig. 12). At the summit of the detritals, the Antietam sands are likewise best developed toward the South Mountains.

If it is correct that the Glenarm series is Cambro-Ordovician in age and not pre-Cambrian, then the Setters quartzite should represent the thinning, transgressive, near-source wedge of the Lower Cambrian detritals.

The dolomites at the summit of the Lower Cambrian in south-central and southeastern Pennsylvania undergo some variations in thickness, but are persistent excepting at the Mine Run anticline (Figs. 5, 11). Their failure at this locality is due to Cambrian activity of the Mine Ridge dome. It is plausible though not wholly certain that the Lower Cambrian dolomites were deposited over this dome, and then upwarped and eroded before deposition of the Early Ordovician Conestoga limestone. Similar Cambrian dome-activity may account for some of the local absences of the Setters quartzite, as at some of the Wissahickon-Baltimore gneiss boundary surfaces east and southeast of Doe Run, Pennsylvania (Fig. 5).

[4] Further information will, however, be required to preclude possibility of major transport from the north across the northeastern part of Pennsylvania, toward the area of coarsest and thickest Hellam conglomerate (Fig. 12).

Middle and Upper Cambrian

Outcrop areas of Middle and Upper Cambrian sediments in New York, Pennsylvania, and Maryland

The horizon of the Middle and Upper Cambrian sediments reaches the surface in New York, Pennsylvania, and Maryland chiefly in the following areas (Fig. 16).

1. Flanks of Adirondack Mountains in northeastern New York, together with small outliers in Adirondacks
2. Hudson River Valley (not detailed in Fig. 16)
3. Limestone valleys in central Pennsylvania
4. Chambersburg and Hagerstown areas of Great Valley of south-central Pennsylvania and central Maryland
5. Southeastern Pennsylvania east of Chambersburg
6. Glenarm region in southeastern Pennsylvania and northeastern Maryland

Characters of the Middle and Upper Cambrian sediments of each of these areas are summarized, and consideration is given to the regional relations, sedimentation, and paleogeography.

Middle and Upper Cambrian along flanks and in small outliers of Adirondack Mountains

General relations

The Potsdam sandstone, which rests upon the eroded surface of the pre-Cambrian complex in the Adirondack region (Figs. 14, 16), was named by Emmons (1838) more than a century ago from exposures near Potsdam in St. Lawrence County, at about the mid-length of the northern margin of the Adirondack Mountains. The sandstone was subsequently traced westward to its wedge-out south of Theresa, near the northeastern tip of Lake Ontario. Eastward, the Potsdam formation persists along the northeastern, eastern, and southeastern flanks of the Adirondacks, until on the southern margin it again wedges out between Saratoga Springs and Little Falls.

In all regions of their occurrence, the Potsdam sandstones are overlain by dolomites, or dolomitic limestones and limestones, in part somewhat sandy, that were termed the "Calciferous" by earlier geologists of New York. The "Calciferous" as a whole is Lower Ordovician Beekmantown in age. Near Saratoga Springs on the southeastern margin of the Adirondacks, however, fossils found in interbedded dolomites and limestones near the junction of Potsdam and "Calciferous" include the dicellocephalid trilobite, *Tellerina hartii*, and other distinctive Upper Cambrian fossils. These fossiliferous, in part somewhat sandy strata were grouped by Walcott with the subjacent Potsdam in the "Saratogan" or Upper Cambrian series. "Saratogan" fossils are also known in somewhat calcareous beds of the upper third of the Potsdam at Ausable Chasm, farther north along the eastern flank of the Adirondacks.

The *Tellerina hartii* limestone at Saratoga Springs has been named Hoyt limestone by Ulrich and Cushing (1910). It is commonly regarded as a local de-

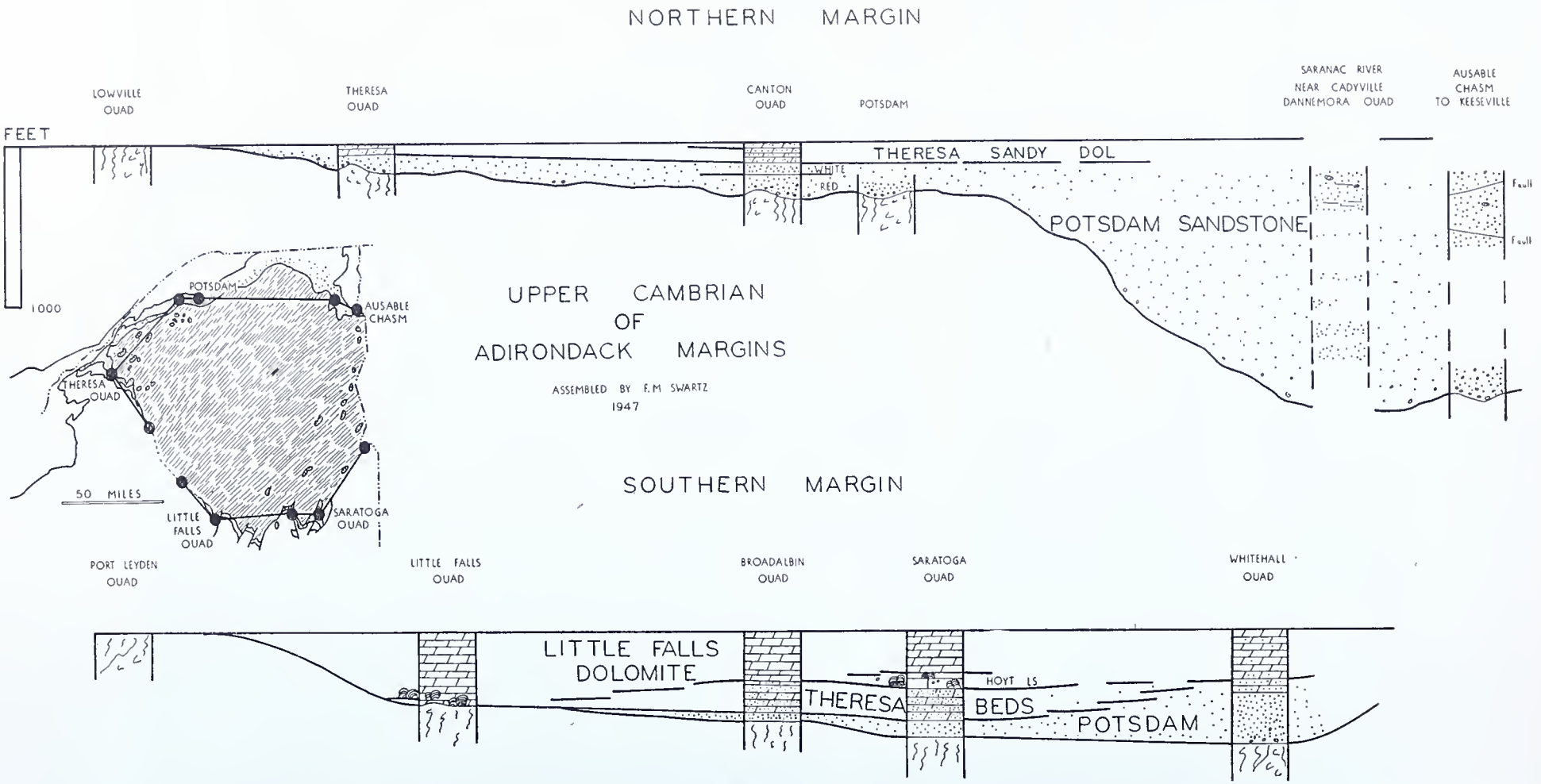


FIG. 14.—Stratigraphy of Upper Cambrian sediments of northern and southern margins of Adirondack Mountains.

velopment in the lower part of the Little Falls dolomite, which is overlain by the sandy Tribes Hill dolomite of early Beekmantown age. Between the Hoyt limestone and Potsdam at Saratoga Springs are sandy dolomites classed as Theresa dolomite by analogy with the type Theresa beds diametrically across the Adirondacks.

The Cambrian rocks of the Adirondack margins thus include, on the north and northwest, the type Theresa dolomite underlain by the type Potsdam sandstone. On the southern margin the type Little Falls dolomite, with its local Hoyt limestone member, is underlain toward the east by sandy Theresa dolomite beds and Potsdam sandstone. The characters of the Potsdam sandstone and of the overlying dolomitic rocks are discussed in turn.

POTSDAM SANDSTONE AND FORM OF PRE-POTSDAM SURFACE

In the vicinity of Potsdam and nearby Canton, northern New York, the Potsdam sandstone ranges to as much as 200 or 300 feet in thickness (Reed, 1934; Chadwick, 1919). Chadwick especially has called attention to marked differences in the upper and lower parts of the Potsdam in its type area. The upper half or so of the formation consists of cleanly washed whitish quartz sandstones or quartzites (Fig. 14). Ripple marks, largely of oscillation type, are relatively common. In marked contrast, the lower beds tend to be feldspathic, pebbly, and are stained red by iron oxide. Pebbles and cobbles of these lower strata consist predominantly of milky quartz and Grenville quartzite, but locally include fragments of granite. According to Chadwick, the basal contact commonly appears to represent a residual, reddish soil, although at other places the contact is sharply defined.

It is the reddish, conglomeratic facies that occurs along the river exposures just south of Potsdam, and so Chadwick has questioned the desirability of extending the term, Potsdam formation, to include the higher, white sandstones. He suggested that the whitish quartzose sandstone might well be distinguished as Keeseville sandstone, named for Keeseville near Ausable Chasm. The quartzose beds, however, typify the Potsdam sandstone as described in the literature.

Both the lower reddish and upper whitish members of the Potsdam vary markedly in thickness in the Potsdam and Canton quadrangles. The irregular distribution seems primarily to result from deposition of the sediments on a surface of moderate relief, in which valleys $\frac{1}{3}$ mile to several miles in width were separated by divides rising as much as 100–200 feet above the valley floors.

Westward toward Alexandria and Theresa, in the Thousand Islands region of New York, the Potsdam sandstone consists chiefly of the whitish, quartzose, ripple-marked facies. Here likewise the Potsdam was deposited on a surface of moderate relief, with divides rising about 100 feet above the valley floors so that the formation thickens and thins in accordance with the topography of the subjacent surface. Some at least of the pre-Potsdam valleys are entrenched in the Grenville limestones. Initial dips of 20–30°, somewhat heightened by differential compaction, occur at places near the slopes of buried hills. Pebble beds are vari-

able in occurrence. Some types may represent old stream channels; others may belong at the foot-regions of sea-cliffs. The pebbles and local cobbles consist mostly of milky quartz; at some places the Grenville quartzites are well represented; fragments of Laurentian granite are common at only a few localities.

South of Theresa, the Potsdam sandstones thin and disappear, and are absent for nearly 100 miles where the pre-Cambrian surface dips beneath the Paleozoics of the southwestern flank of the Adirondacks.

Eastward from Potsdam the Potsdam thickens to 1,000 or possibly 1,500 feet along the northeastern Adirondack margin. Here also there are, in general, lower reddish and feldspathic sandstones and conglomerates, overlain by whitish quartzites, and then by calcareous or dolomitic sandstones. Near Ausable Chasm the lower beds include coarse conglomerates and red conglomeratic sandstones containing quartz, quartzite, and gneissic fragments, that were deposited on a surface with several observed ridges and bosses of anorthosite. The conglomerates are overlain by reddish, feldspathic sandstones of finer grain. Overlying beds exposed in the chasm consist of cleaner quartzose sand, in part quartzitic, in part somewhat calcareous and containing scattered pebbles of dolomite and shale. Fossils are moderately common through at least 100 feet of the calcareous strata, and include some trilobites together with *Lingulepsis acuminata* and other phosphatic brachiopoda.

Farther south, the Potsdam deposits thin once more, and are approximately 400 feet in thickness near Whitehall, 100 feet near Saratoga Springs. As near Theresa on the northwest margin of the Adirondacks, the thinned Potsdam on the southeast near Saratoga Springs consists mostly of the whitish, quartzitic facies. Westward from Saratoga, the Potsdam wedges out and disappears before reaching Little Falls.

About a half-dozen outliers of the Potsdam sandstone have been discovered in the southeastern part of the Adirondacks, a dozen or more in the northwestern region. In the southeast, a few of these small, isolated patches are 15–25 miles from the flanking Potsdam outcrops. The known occurrences represent the whitish, quartzose facies of the formation. They occur to-day in deep valleys of the mountain region. It is difficult to be certain whether they have been lowered in down-faulted blocks, or occur as remnants in the floors of ancient, deep pre-Potsdam embayments.

THERESA AND LITTLE FALLS DOLOMITES AND HOYT LIMESTONE

The Theresa dolomite, where it lies above the Potsdam sandstone along the northwestern and northern borders of the Adirondacks, ranges from approximately 30 to possibly 100 feet in thickness. It consists throughout of dolomites and sandy dolomites, with thin interbeds of sandstone. Near Canton, a 25-foot body of sandstone at the top of the Theresa was recognized by Chadwick as Huevelton sandstone. It is a locally mappable horizon, but represents little change in sedimentary conditions.

Across the entire northern border of the Adirondacks, the Theresa beds are recognized by their characteristic "sand crystals." On the broken surface of the rock, lustrous curved cleavage faces of $\frac{1}{2}$-inch crystals of dolomite are speckled with sparse, embedded grains of quartz sand.

The phosphatic brachiopod, *Lingulepsis acuminata*, has been discovered in Theresa strata at some localities in the Thousand Islands region. In general, however, fossils are rare and poorly preserved.

The Theresa dolomites are transitional with the underlying Potsdam sandstone. The uppermost Potsdam beds are dolomitic and grade into the sandy dolomites of the Theresa formation.

The uppermost 20–30 feet of sandy dolomite included in the Theresa formation, when it originally was defined, have subsequently been classed as Tribes Hill and referred to the Early Ordovician Beekmantown group. This treatment is based principally on rare *Ophileta complanata* ("*Pleurotomaria hunterensis*"). The Theresa-Tribes Hill boundary is obscure, and gives no apparent evidence of significant change in paleogeography or in conditions of deposition.

On the southeastern border of the Adirondacks, the beds classed as Theresa dolomite are 50–150 feet thick. They consist of alternating sandstones and sandy dolomites, transitional with the Potsdam sandstone on which they rest.

The Theresa beds give way above to the less sandy Little Falls dolomite, which is transgressive upon the Potsdam and Theresa so that at Little Falls it rests directly on the pre-Cambrian crystallines. The Little Falls dolomite is 200–500 feet thick from the New York-Vermont border to Little Falls, but wedges out westward, disappearing before reaching the Port Leyden Quadrangle (Fig. 14). In general, the formation is composed of thick-bedded, gray, finely crystalline dolomite. Some parts are cherty, and there are local sandy lenses. Drusy cavities occur in moderate numbers. Some of these have a first lining of anthracite-like material, believed to be an asphaltic derivative. This lining is covered toward the inside of the cavity, by minute crystals of dolomite, and on these in turn there commonly are crystals of quartz and calcite.

Fossils generally are rare in the Little Falls. There are local lenticular reefs of the calcareous algal deposits termed *Cryptozoön*, and some silicified reefs occur near the top of the formation.

More fossiliferous, lower beds of the Little Falls near Saratoga Springs were named Hoyt limestone by Ulrich and Cushing in 1911. These strata contain the distinctive Upper Cambrian *Tellerina hartii* fauna, with several additional, associated trilobites, some snails, and *Lingulepsis acuminata* and other phosphatic brachiopods.

The Hoyt limestone contains three extensive, successive *Cryptozoön* reef-beds, finely exposed at the "Petrified Gardens" at Ritchie Park and elsewhere near Saratoga Springs. Each of the three reefs is dominated by its own particular *Cryptozoön* species.

The reef layers are commonly 2–4 feet in thickness. Each reef appears to repre-

sent the culmination of a stratigraphic succession or cyclothem that begins with 1–5 feet of quartz sandstone having little calcium carbonate, then a few feet of sandy dolomite, then the 2- to 4-foot reef-layer, in places associated at its base with oölitic limestone, then more dolomite that generally is somewhat sandy and in part may be thin-bedded.

Lithologically, the Hoyt formation includes dark, dense to finely crystalline limestone and alternating beds of grayish dolomites, together with sandy dolomites and dolomitic or calcareous sandstones, some quartzose sandstones and, especially near the base, some black oölitic limestone.

MIDDLE AND UPPER CAMBRIAN OF HUDSON RIVER VALLEY

Some fossils of the Upper Cambrian dicellocephalid faunas have been discovered near Newburgh and Poughkeepsie in the limestones mapped as Wappinger terrane (for location of Wappinger outcrops see Fig. 12). Other parts of the Wappinger, however, contain the Lower Cambrian *Olenellus* fauna, and Ordovician fossils likewise have been found. The Wappinger rocks are thus a complex, and only a small part of their estimated 1,000 feet thickness can be Upper Cambrian in age.

In the Taconic plate, overthrust into its present position near Albany, Upper Cambrian sediments are absent by unconformity at all of the known, unfaulted junctions of Cambrian and Ordovician strata. In general, at these places the Lower Ordovician Deepkill and Schaghticoke shales rest on the moderately folded and eroded edges of the Lower Cambrian Schodack. In Stissing Mountain in northern Dutchess County the thin, local Stissing limestone may be Middle Cambrian in age.

MIDDLE AND UPPER CAMBRIAN OF NITTANY VALLEY AND MORRISON AND FRIENDS COVES IN CENTRAL PENNSYLVANIA

Middle and Upper Cambrian deposits, reaching thicknesses of 3,000 –4,000 feet, are exposed along the axial parts of anticlinal Nittany Valley and Morrison and Friends Coves from central to south-central Pennsylvania (Butts, 1936, 1939, 1945). For the most part, the sediments are dolomites and limestones, with subordinate sandstones that occur chiefly in the Gatesburg formation, and some chert. Shale beds are few, though some of the limestones are argillaceous (Fig. 15).

The oldest strata exposed in the three anticlinal valleys are 200 feet of greenish and dark gray, in part purplish shales, containing some interlayers of greenish micaceous sandstone, some of quartz sandstone, and a few of pea-sized quartz-pebble conglomerate. These sediments contain fragments of *Olenellus* and *Bonnia*, that give evidence of Lower Cambrian age. Because of their general stratigraphic position, and their sandy, in part purplish shales, they have tentatively been correlated with the Waynesboro formation of the Chambersburg region. Fossils have not been found in the Waynesboro in its type region, and it is not impossible

that the supposed Waynesboro of Morrison Cove will be proved equivalent to pre-Waynesboro sediments of the Chambersburg region.

The Pleasant Hill formation contains trilobites of the Middle Cambrian *Alokistocare, Olenoides* fauna. Of its 600 feet of strata, the lower 200 feet are composed of thin-bedded, argillaceous and somewhat micaceous limestones. The higher part is thick-bedded, somewhat purer bluish limestone. Many of these layers, however, have variations in composition, so that on weathering they become peculiarly mottled and "worm-eaten" in appearance; the reopened tubes may actually reflect extensive worm burrows of the ancient calcareous sediments.

Above the Middle Cambrian Pleasant Hill limestone, the Upper Cambrian includes the Warrior limestone, Gatesburg dolomite, and Mines dolomite, totalling 2,500–3,000 feet in thickness. The limestones of the 1,200 feet of Warrior limestone vary from fairly pure to argillaceous and micaceous; dolomitic interlayers are numerous; beds of oölitic limestone recur at a good many horizons, and some of these contain trilobite fragments. *Cryptozoön* reefs are fairly common. Some of the reefs form irregular mounds, but they rarely are more than 5 or 6 feet in greatest thickness.

At Williamsburg in the Huntingdon Quadrangle, the Warrior contains two sandy beds that project as prominent, backbone-like ledges from the northern bank of the Juniata River. The upper of these beds is an arenaceous limestone, approximately 10 feet thick and lying 550 feet stratigraphically below the top of the formation. The second, 75 feet lower, is cored by 6 feet of quartzite. Some of the adjacent dolomite and limestone beds are more sparingly arenaceous, and there are approximately 50 feet of sandy dolomite 180–230 feet above the base of the formation. The sand grains of the two prominent ledges are well rounded to somewhat subangular, commonly 0.1 to 1 millimeter in diameter. Non-quartz grains are rare. The sandstones disappear toward the northwest in the Tyrone and Bellefonte quadrangles.

There is a local absence of the Warrior near Grazier Mill in the Tyrone Quadrangle. Butts (1939) was inclined to attribute this to local warping of the floor of deposition rather than to Appalachian faulting, though he did not regard his evidence as being conclusive.

Species of the early Upper Cambrian trilobites *Blountia, Coosella,* and *Kingstonia* have been described from the Warrior, mostly from beds of the middle and upper parts of the formation. The writer has a *Crepicephalus* tail from the beds near Waddle northeast of State College.

Ascending in the stratigraphic succession, the limestones, argillaceous limestones, dolomites, and dolomitic limestones of the Warrior give place to the 1,600 feet of gray dolomites and thin quartzites of the Gatesburg formation. South of Williamsburg in Morrison Cove, the lower 500 feet of the Gatesburg consist almost wholly of medium-textured, crystalline gray dolomite, without quartzite. In higher parts of the formation, there are numerous interbeds of pure quartz sandstone or quartzite, commonly ranging from 1 to 10 feet in thickness and form-

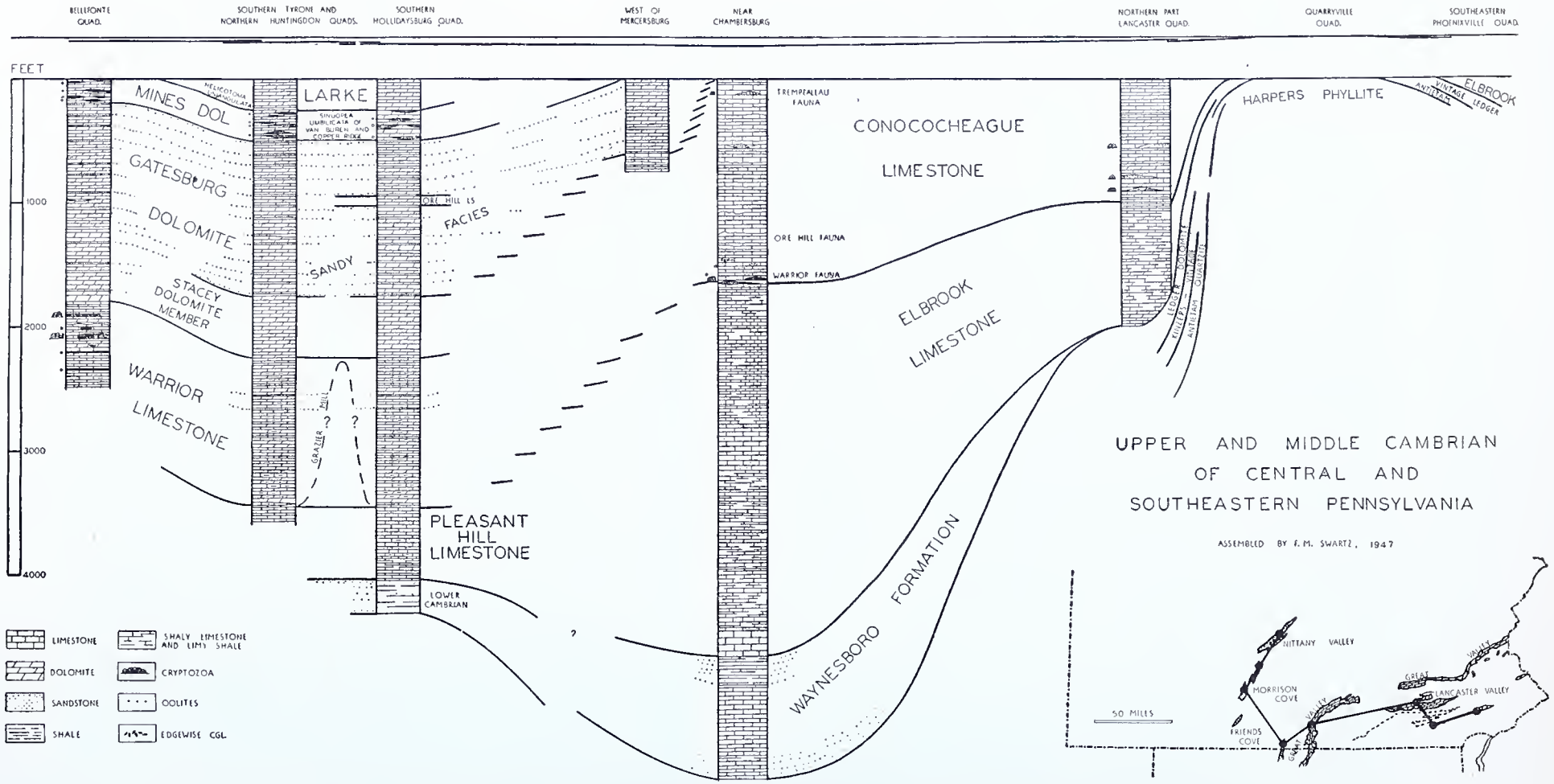


FIG. 15.—Stratigraphy of Middle and Upper Cambrian sediments from central Pennsylvania to south-central and southeastern Pennsylvania. Diagram at top of figure shows over-all thickness changes at true vertical scale. Larke dolomite probably should be included in Lower Ordovician Beekmantown group, and Mines likewise has been so classed by some authors. Waynesboro formation may be Lower Cambrian throughout.

ing 10–15 per cent of the mass. Many of the dolomite layers are dark, medium-textured crystalline; others are thinner-bedded, lighter-colored and finer-textured. Some of the dolomites are oölitic and some are sandy. Pelto (1942) found that near Birmingham in the Tyrone Quadrangle, these facies occur in repeated cycles, in which thin quartzitic sandstones are overlain by thin-bedded to thick-bedded dark dolomite, culminating in some places in *Cryptozoön* layers which are underlain by oölitic dolomite, and generally overlain by buff silty and sandy dolomite.

Approximately 500–600 feet below the summit of the Gatesburg in Morrison and Friends Coves there is a 100-foot body of limestone named the Ore Hill member by Butts. This limestone contains a large suite of trilobites, including *Elvinia roemeri* of the Theresa of New York; *Plethopeltis*, *Saratogia*, and *Pelagiella* of the Hoyt limestone of New York; *Conaspis*, *Elvinia*, *Burnetia*, *Irvingella*, and *Housia* of the Franconia of Wisconsin. James L. Wilson (personal communication, 1947) comments that the *Conaspis* fauna of higher beds of the Ore Hill corresponds with the fauna of the Goodenough member of the Franconia, and that the *Elvinia* fauna occurs in a distinct zone and shows equivalence with the Ironton member of the Franconia. In the lower part of the Ore Hill is a third faunal zone that is duplicated approximately 300 feet above the base of the Conococheague near Chambersburg.

The Ore Hill limestone disappears northeastward in the Tyrone and Bellefonte quadrangle regions of Nittany Valley, apparently by intergradation into dolomite. The quartzitic sandstone interlayers and cyclic character of the Gatesburg persist from Nittany Valley to Friends Cove, with appearance of some calcareous interbeds in the section studied by Wilson in Friends Cove.

At the top of the Gatesburg, quartzite interbeds disappear, and are lacking in the overlying 250 feet of Mines dolomite. The dolomites of the Mines are dark gray and thick-bedded like many of those of the Gatesburg; however, they not only lack the quartzites of the Gatesburg but contain much oölitic chert, which is rare in the Gatesburg formation. Some of the cherts of the Mines are silicified *Cryptozoöns*.

In addition to species of *Cryptozoön*, the Mines has yielded some gastropods, including *Sinuopea* closely similar to *S. umbilicata* of the Copper Ridge dolomite of Alabama. The Mines is correlated by Howell (1944) with the *Saukiella-Cavinella* zone of the Trempealeau of Wisconsin, the higher part of the Conococheague near Chambersburg, and with part of the Copper Ridge dolomite of Alabama.

The Larke dolomite, which overlies the Mines dolomite near Williamsburg in the Huntingdon Quadrangle, consists of approximately 250 feet of thick-bedded, rather coarsely textured, crystalline grayish dolomite with very minor chert and only a few thin sandy interlayers. Butts has identified *Helicotoma uniangulata* in the collections from the Mines. This species was first discovered near Saratoga Springs, New York, in cherts believed to come from the upper part of the Little Falls dolomite. The Larke dolomite is latest Upper Cambrian or earliest Lower Ordovician in age.

MIDDLE AND UPPER CAMBRIAN OF GREAT VALLEY NEAR CHAMBERSBURG AND HAGERSTOWN

Marked changes occur in the Middle and Upper Cambrian strata as they are traced from the anticlinal limestone valleys of central Pennsylvania to the more southeastern Great Valley region near Chambersburg, Pennsylvania, and Hagerstown, Maryland (Stose, 1910; Bassler, 1919; Stose and Bascom, 1929). The sediments thicken; there is increase in volume of argillaceous limestones that grade into calcareous shales; dolomites and sandstones are reduced (middle part of Fig. 15).

The Waynesboro formation, 1,000 feet thick at the bottom of this sequence, has been variously classed as Middle Cambrian and as Lower Cambrian. The latter treatment is probably preferable; the formation has not, however, yielded fossils in the Chambersburg-Hagerstown region, excepting phosphatic brachiopods of *Lingulella* type, and these are of little help in close correlation. The formation seems to be traceable southwestward into the Rome formation of Virginia, which in part at least contains *Olenellus* and definitely is Lower Cambrian in age. Near Chambersburg and Hagerstown, the Waynesboro formation lies above the Tomstown dolomite which contains *Olenellus* and rests on the *Olenellus* beds of the uppermost Antietam.

The Waynesboro formation near Chambersburg and Hagerstown consists of a lower member of gray limestone and calcareous sandstone, a middle member of limestone, and an upper member of purplish to reddish silty shale and argillaceous sandstone. The upper layers are marked by ripple marks and mud cracks.

The Elbrook formation, 3,000 feet thick, consists dominantly of argillaceous limestone and calcareous shale. There are approximately 100 feet of dark blue, thick-bedded, sparingly fossiliferous limestone at the base, overlain by approximately 1,000 feet of minutely laminate shaly limestone and calcareous, greenish and partly purplish shale. At the middle of the formation are some knoll-forming siliceous limestones and thick-bedded dolomites. The upper half of the formation consists of argillaceous limestone and calcareous shale, weathering into fragments which are more blocky than those in the lower shaly member.

The trilobites of the basal limestones of the Elbrook include *Glossopleura bassleri* which is also found in the early Middle Cambrian Rutledge shale of the western side of the Great Valley of southwestern Virginia and northeastern Tennessee. Of higher parts of the Elbrook, much plausibly is Middle Cambrian; but the highest beds may well be Upper Cambrian, possibly corresponding with part of the argillaceous Warrior limestone of central Pennsylvania.

The Conococheague limestone, approximately 1,600 feet thick, forms the bulk of the Upper Cambrian near Chambersburg and Hagerstown. It is composed for the most part of dark blue, banded limestones, containing numerous thin, generally wavy silty laminae that stand in relief on the weathered surfaces. Beds of edgewise limestone conglomerate, in which 2- to 6-inch wide, thin plates of limestone are jumbled together in a limestone matrix, occur at many levels. There

are minor oölitic limestones. Chert is common at some horizons, and some in the lower part of the formation weathers to rough, scoriaceous boulders. Some limestones in the upper 400 feet are purer, pinkish, crystalline and marble-like.

In the lower 250 feet, especially, of the Conococheague there are *Cryptozoön* reef-masses formed by the species, *C. proliferum* and *C. undulatum*, that likewise occur in reefs of the Hoyt limestone in New York. As at other localities, oölitic limestones are associated with the reefs.

On the western side of the Great Valley, west of Chambersburg, the upper 600 feet of the Conococheague contain interbeds of massive sandy dolomites and sandstones, some of them when weathered coherent enough to have been a local source of grindstones.

Bassler (1915) reported the brachiopod *Eoorthis* and dicellocephalid trilobite *Saukia stosei* from the upper beds of the Conococheague, and Resser (1938) termed this the *Tellerina* fauna. James L. Wilson (personal communication, (1947) reports that the fauna of the upper Conococheague is Trempealeau in age, that the lowest of the three trilobite faunas of the Ore Hill member of the Gatesburg of Morrison and Friends Coves occurs approximately 300 feet above the base of the Conococheague near Chambersburg, and that a fauna of Warrior age has been discovered at the base of the Conococheague. These discoveries further document Butts' correlation of the Gatesburg with the greater part of the Conococheague, and show that the Upper Cambrian sandy dolomites of central Pennsylvania interfinger with and grade laterally into the silty, somewhat cherty limestones on the southeast.

MIDDLE AND UPPER CAMBRIAN IN SOUTHEASTERN PENNSYLVANIA EAST OF CHAMBERSBURG

The Waynesboro formation is absent everywhere in southeastern Pennsylvania east of the Chambersburg region; but the Elbrook and Conococheague persist without much lithologic change though with some reduction in thickness into the northern part of the Lancaster Quadrangle (Fig. 15), and into the Reading Prong farther northeast.

In the northern part of the Lancaster Quadrangle, the Elbrook limestone is approximately 1,000 feet thick, and consists of thin-bedded argillaceous limestone and whitish to cream-colored marble with sericitic partings. The Conococheague likewise is approximately 1,000 feet in thickness. It consists of the characteristic light blue limestone with silty laminae, together with some fine-textured whitish marbles and some dolomite. *Cryptozoön* reef beds are fairly common.

Near Reading, Willard and Frazer (1939) report 1,000 feet of Elbrook limestone, consisting of massive bluish gray magnesian limestone with chert bands, and 1,000–1,500 feet of Conococheague limestone, composed of bluish gray limestone with silty or sandy laminae. *Cryptozoön* beds occur in the Conococheague. In Lehigh County, Miller (1941) included the Conococheague and possibly some Elbrook beds in the Allentown limestone.

In contrast to the general eastward and northeastward persistence of the Elbrook and Conococheague from Chambersburg to the northern part of the Lancaster Quadrangle and to the Reading Prong, there is abrupt disappearance of these formations southward from Lancaster to the Mine Ridge region of the Quarryville Quadrangle (Figs. 5, 15). In the valleys flanking Mine Ridge not only the Elbrook and Conococheague disappear, but also the Lower Cambrian Vintage, Kinzers, and Ledger. There has been some question whether part of the Upper Cambrian formations may be represented in the basal part of the Conestoga limestone of Chester Valley (compare Fig. 19); however, the Conestoga is relatively thin, and in part at least is Beekmantown in age according to fossil discoveries. Furthermore, the Vintage, Kinzers, Ledger, and Elbrook reappear beneath the Conestoga farther east in Chester Valley (Figs. 5, 15). Hence, it is reasonably certain that in the vicinity of Mine Ridge and the western part of Chester Valley, the late Lower Cambrian, Middle Cambrian, and most or all of the Upper Cambrian disappear by unconformity beneath the Conestoga. It is not now clear, however, whether this resulted from non-deposition, or from deposition followed by pre-Conestoga uplift and erosion.

POSSIBLE MIDDLE AND UPPER CAMBRIAN OF GLENARM REGION

If the Glenarm rocks of the region south of Chester Valley (Figs. 5, 6) are Cambro-Ordovician in age, it may be that some later Cambrian sediments occur in that region. If so, they presumably would form part of the Cockeysville marble. It is probable, however, that the Cockeysville corresponds with the Conestoga of Chester Valley, and that it is for the most part Beekmantown in age.

REGIONAL RELATIONS, SEDIMENTATION, AND PALEOGEOGRAPHY OF MIDDLE AND UPPER CAMBRIAN DEPOSITS IN NEW YORK, PENNSYLVANIA, AND MARYLAND

BASIC DATA

The data summarized in the stratigraphic charts of Figures 14 and 15 and discussed on accompanying pages, are reëxpressed in the isopachous map (Fig. 16) to illustrate in preliminary fashion the major changes in thickness of Middle and Upper Cambrian sediments of outcrop regions in New York, Pennsylvania, and Maryland. Significant areas of sand accumulation are shown by stippling.

Conditions of sedimentation suggested by these data are also pictured, though with interpretative geological license, in the paleogeographical diagrams of Figure 17. The regional relations, sedimentation, and paleogeography of the Middle Cambrian and the Upper Cambrian of the region are to be discussed in turn with use of all of these charts and maps.

MIDDLE CAMBRIAN

During Middle Cambrian time, the depositional areas of the Appalachian trough were less extensive than in the Lower Cambrian (Fig. 17A). Neighboring

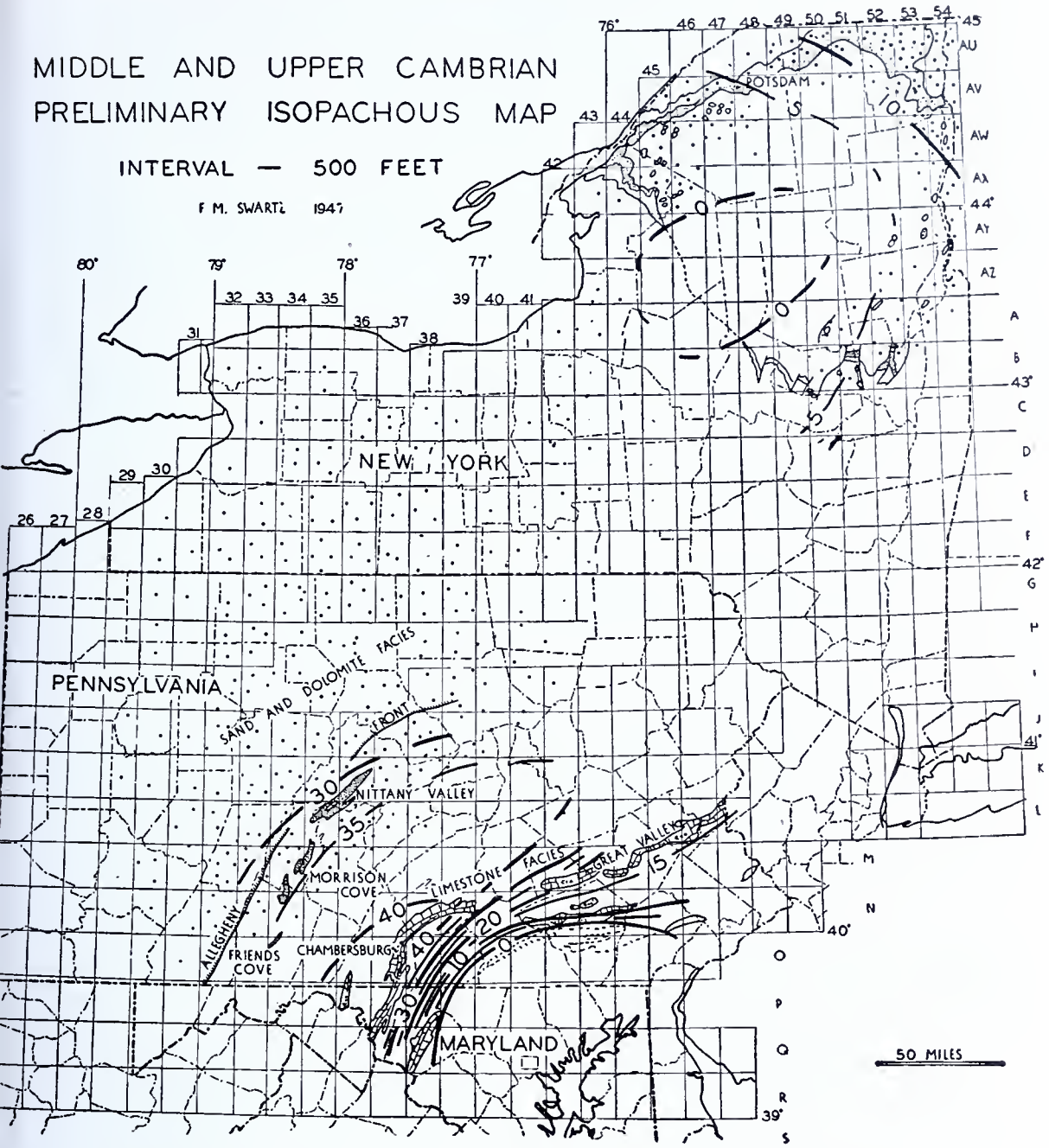


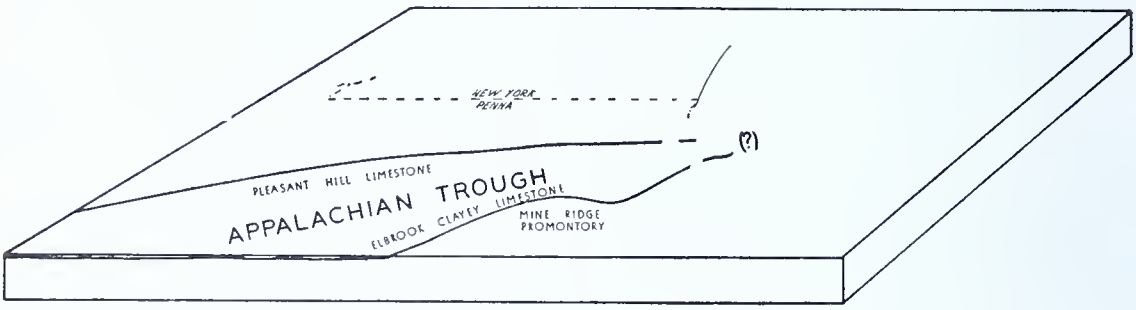
FIG. 16.—Preliminary isopachous map for combined Middle and Upper Cambrian sediments of New York, Pennsylvania, and Maryland. Significant sand accumulations shown by stippling. For location of Wappinger terrane outcrops, see Figure 12.

lands, furthermore, had been lowered and supplied no counterpart of the great volume of Lower Cambrian sand and clay sediments.

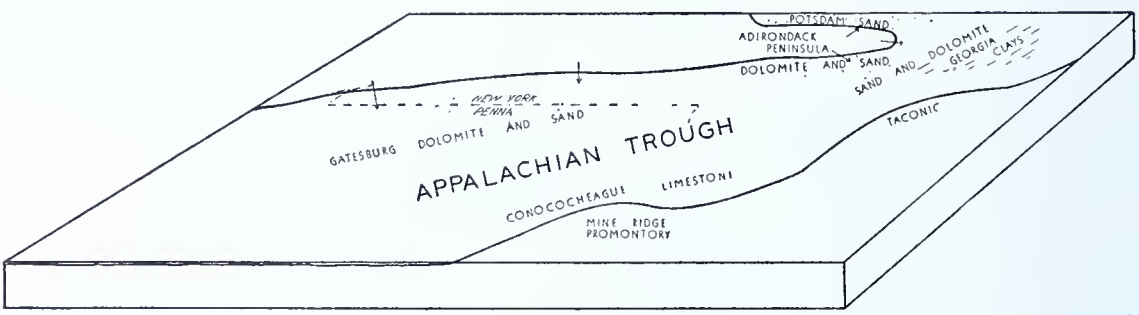
As in the Lower Cambrian, sediments of Middle Cambrian age are lacking along the flanks of the Adirondack Mountains, unless some of the earlier parts of the thick Potsdam sands of the northeastern Adirondack margin may have accumulated at this time.

East of the Adirondacks, in Vermont beyond the New York border, Middle Cambrian deposits are thin and very limited in extent. Middle Cambrian sediments have not been identified in the autochthonous rocks of the Hudson River Valley of New York. The Vermont and southeastern New York regions that were extensively flooded during lower Cambrian time, seem to have been emergent during much of the Middle Cambrian.

The Elbrook deposits, stretching from the Reading Prong region of eastern Pennsylvania to Lancaster and then to the Chambersburg-Hagerstown region



A. PLAUSIBLE PALEOGEOGRAPHY OF MIDDLE CAMBRIAN SEDIMENTATION



B. PLAUSIBLE PALEOGEOGRAPHY OF UPPER CAMBRIAN SEDIMENTATION.

FIG. 17.—Plausible paleogeography of Middle Cambrian and Upper Cambrian sedimentation in New York, Pennsylvania, and Maryland.

of south-central Pennsylvania and central Maryland, form the main known relic of the Middle Cambrian seas that crossed these states. More northwesterly reaches of the sea are represented by the Pleasant Hill limestone of Morrison Cove.

Both the Elbrook and Pleasant Hill plausibly were deposited in extensive, shallow seas, though fossil shells are uncommon. The Pleasant Hill limestone on the northwest is fairly pure, splotched as though by lime-filled burrows of numerous sea-floor worms. On the south and southeast, the Elbrook limestones contain much clay. Geographic relations with the Pleasant Hill suggest that the

source-land of the clay may have been southeast; but detailed correlations and present knowledge of lateral changes are insufficient to establish the direction of transport.

Disappearance of the Elbrook and additional Cambrian sediments below the Conestoga limestone near Mine Ridge in southeastern Pennsylvania gives record of crustal activity in that area during Cambrian time. Either the Mine Ridge promontory shown in Figure 17A was emergent during Elbrook time, or else Elbrook sediments were deposited and then elevated and eroded before the Conestoga sediments began to accumulate.

The sandy, argillaceous, and calcareous sediments of the lower and upper parts of the Waynesboro formation near Chambersburg and Hagerstown indicate a brief increase in erosion of some adjacent emergent area, either at the close of Lower Cambrian or beginning of Middle Cambrian time. Location of the source-land is not established, but may well have been eastward toward the crustally active Mine Ridge and Glenarm regions.

UPPER CAMBRIAN

In Upper Cambrian time, the Appalachian seas spread progressively beyond their earlier confines, and deposited thick sediments in the New York, Pennsylvania, and Maryland region (Figs. 14, 15, 17). Sands accumulated along the northern, eastern, and southeastern margins of an Adirondack peninsula that may have become an island but at least did not wholly submerge during even the farthest encroachment of the Cambrian seas. In Pennsylvania and western New York, quartz sands filtered from the northwest into the northwestern part of the Appalachian trough, and here the thick associated carbonates are mostly dolomites. Along the southeastern section of the trough, the dolomitic and sandy sediments give place to limestones containing thin laminae of silt and moderate amounts of chert.

Throughout the region of deposition, waters seemingly were shallow, and excepting near the Adirondacks were spread upon a nearly flat surface of sedimentary accumulation. In the Hoyt limestone of New York and Gatesburg dolomite of Pennsylvania, slight fluctuations in sea depth produced recurrent, cyclic deposits in the order: sand—dolomite—*Cryptozoön* reef—dolomite. These cycles plausibly reflect repeated gentle subsidence, followed by sedimentary upbuilding possibly with some uplift. Distances of transport of sand into the basin during deposition of the thin sand interlayers, and paucity of associated clays are both notable.

In the Conococheague deposits of the limestone belt, *Cryptozoön* reef beds are relatively common. Oölitic limestones are in part associated with the reefs. Recurrent, edgewise limestone conglomerates reflect shallowing of the water and brief emergences of tidal flats.

Along the northern, eastern, and southeastern flanks of the Adirondack region, initial red-stained feldspathic sands and conglomerates, plausibly of alluvial-lagoonal facies, were succeeded by well washed, ripple-marked quartz sands of

littoral type. Though the reddish feldspathic sands everywhere underlie the quartzose sands, the two facies actually may interfinger. If the change to beach conditions was progressive through the region, parts of the alluvial-lagoonal reddish sands may be equivalent to parts of the quartzose sands winnowed by surf and shore currents. Some local feldspathic conglomerates may represent rapidly accumulated shingle bordering wave-cut bluffs.

The Potsdam sands of the Adirondack margins accumulated upon the submerging surface of the pre-Cambrian complex. The surface was one of low relief, with hills and ridges rising 100 to possibly 200 feet above the floors of near-by valleys. Chadwick has reported residual soil in some places at the Potsdam, pre-Cambrian contact.

Much of the Potsdam sand of the Adirondack flanks seems to have been derived from the Adirondack peninsula. On the eastern Adirondack margin, lateral changes in Upper Cambrian sandy dolomites of Vermont suggest that the sand came from the Adirondacks.

The sandstone interbeds of the Gatesburg of central Pennsylvania are widespread, and extend far south along the anticlinal valleys. Their distribution suggests derivation from land surfaces north and northwest, and not from the moderate-sized Adirondack promontory on the northeast. The Gatesburg, like the Potsdam, received little clay from its source lands. Cambrian soil surfaces lacked the protective vegetative coverings of later geologic ages, and presumably were more subject to wind deflation. Wind transport of fine rock débris in one direction, at times of water transport of sand along other paths, may have helped produce sedimentary distributions peculiar for our modern world. Evidence is not available for evaluation of this factor in preliminary sorting of the Gatesburg sands.

In southeastern Pennsylvania, the Mine Ridge promontory of Figure 17B is suggested by the disappearance of the Upper Cambrian in that region, by unconformity beneath the Conestoga limestone. The emergent surface may have been an updomed island rather than a land-connected promontory Most of the Glenarm region may likewise have been land.

Lower Ordovician

Outcrop areas of lower Ordovician Beekmantown sediments in New York, Pennsylvania, and Maryland

The "Calciferous sandrock," described by the earlier New York geologists in the limestone regions of the Champlain and Mohawk valleys, has mostly proved to belong to the Lower Ordovician Beekmantown group as named by Clarke and Schuchert in 1899. The name Beekmantown is derived from a town in the northeastern corner of New York, northeast of the Adirondacks.

The belts of outcrop of Beekmantown sediments in New York, Pennsylvania, and Maryland are as follows.

1. Eastern and northern margins of Adirondacks
2. Southern margin of Adirondacks

3. Hudson River Valley
4. Anticlinal limestone valleys of central Pennsylvania
5. Great Valley region near Chambersburg, Pennsylvania, and Hagerstown, Maryland
6. Great Valley, and Lancaster and Chester valleys in Pennsylvania east of Chambersburg region
7. Glenarm region

The Beekmantown sediments of each of these belts are discussed in turn, and the regional relations, sedimentation, and paleogeography are considered.

BEEKMANTOWN OF EASTERN AND NORTHERN MARGINS OF ADIRONDACKS

Lower Ordovician Beekmantown sediments occur in large thickness along the eastern margin of the Adirondacks, from the vicinity of Beekmantown in the northeastern corner of New York, to Shoreham in Vermont (Fig. 18). The latter locality affords excellent exposures that were described by Brainerd and Seely (1890), and furnishes the basis for division of the Beekmantown group now employed in the Lake Champlain region.

In their original description of the Shoreham section, Brainerd and Seely recognized five main subdivisions of the "Calciferous," and in ascending order designated them A, B, C, D, and E. Division A is now regarded as belonging in the Upper Cambrian, excepting possibly the uppermost few feet. Divisions B to E constitute the Beekmantown of the Shoreham section. Division E was grouped with D3 and D4 by Cushing (1905) in the Cassin formation named from Fort Cassin, Vermont, where fossiliferous beds contain the *Eurystomites kellogi*, *Plethospira cassina* fauna. Division B was combined by Rodgers (1937) with a few feet of uppermost A in the Whitehall formation named from Whitehall, New York. Cady (1945), however, has found it preferable to use the divisions established by Brainerd and Seely, and for them uses the names Shelburne, Cutting, Bascom, and Bridport.

The Shoreham section is summarized from Brainerd and Seely's description, with faunal notations from Cady.

	Thickness (Feet)
Lower Ordovician or Canadian	
Beekmantown group	
Bridport dolomite	
(E) Fine-grained magnesian limestone, weathering drab, yellowish, or brown, and some purer limestone. *Bucania tripla, Bathyurus glandicephalus*	470
Thickness of Bridport limestone	470
Bascom limestone	
(D4) Blue limestone and interbedded slaty layers. With D3, this is zone of *Maclurites affinis, M. matutinus, Hystricurus conicus, Isoteloides whitfieldi.* At Fort Cassin equivalent strata contain *Eurystomites kellogi, Plethospira cassina*	100
(D3) Sandy limestone, thin-bedded	120
(D2) Drab and brownish, magnesian limestone, some sandstone near middle	75
(D1) Bluish limestone, some calcareous sandstone. Differential weathering of dolomitic matter irregularly distributed in limestones gives weathered surfaces peculiarly "curdled" appearance. Zonal fossil, *Lecanospira compacta,* occurs in D1, and possibly also in D2 and C4	80
Thickness of Bascom limestone	357

	Thickness (Feet)
Cutting dolomite	
(C4) Magnesian limestone, some black chert	120
(C3) Sandstones, commonly calcareous and dolomitic	70
(C2) Thick-bedded magnesian limestone, weathering drab	100
(C1) Gray, fine-grained, laminated calcareous sandstone. *Ophileta complanata* reported in Cutting above basal sandstones	60
Thickness of Cutting dolomite	350
Shelburne formation	
(B) Thick-bedded, dove-colored limestone and interbedded gray dolomite, transformed to light-colored marble in Shelburne region. *Orthoceras (?) primigenium*	295
Thickness of Shelburne formation	295
Thickness of Beekmantown group	1,525

The rock divisions recognized in the Beekmantown at Shoreham continue toward Beekmantown, New York, with some reduction in thickness and changes in proportions of the limestone-dolomite-sandstone facies. Further marked thinning occurs westward along the northern margin of the Adirondacks, so that in the Thousand Islands region the Beekmantown is represented on the north by approximately 120 feet of Ogdensburg limestone of late Beekmantown age, and near Theresa by 20–40 feet of supposed Tribes Hill sandy dolomite questionably of early Beekmantown age. South of Theresa, even these questionably identified, early Beekmantown strata are lacking along the western margin of the Adirondacks.

Sands associated with the *Ophileta complanata* fauna of the lower Beekmantown increase westward and decrease eastward. They are especially developed near Beekmantown. Their distribution suggests a source area of erosion centering in the regon of the present Adirondacks. Similar relations are observed in scattered sands of the *Lecanospira compacta* zone. On the other hand, slaty terranes near Oak Hill, Vermont, appear to represent clays brought in from the eastern rather than the western margin of the ancient Champlain part of the Appalachian trough of deposition.

BEEKMANTOWN OF SOUTHERN MARGIN OF ADIRONDACKS

Southwestward from Shoreham, Vermont, the Beekmantown limestones rapidly disappear by unconformity, so that no trace of them is found at Saratoga Springs, New York (Fig. 18).

Farther west, at Tribes Hill in the Mohawk Valley, the Late Cambrian Little Falls dolomite is overlain by 40 feet of sandy limestones containing *Ophileta complanata*, *Eccyliomphalus multiseptarius*, and species of asaphid trilobites, all of which give evidence of early Beekmantown age. The sandy limestone was named Tribes Hill limestone by Ulrich and Cushing (1911).

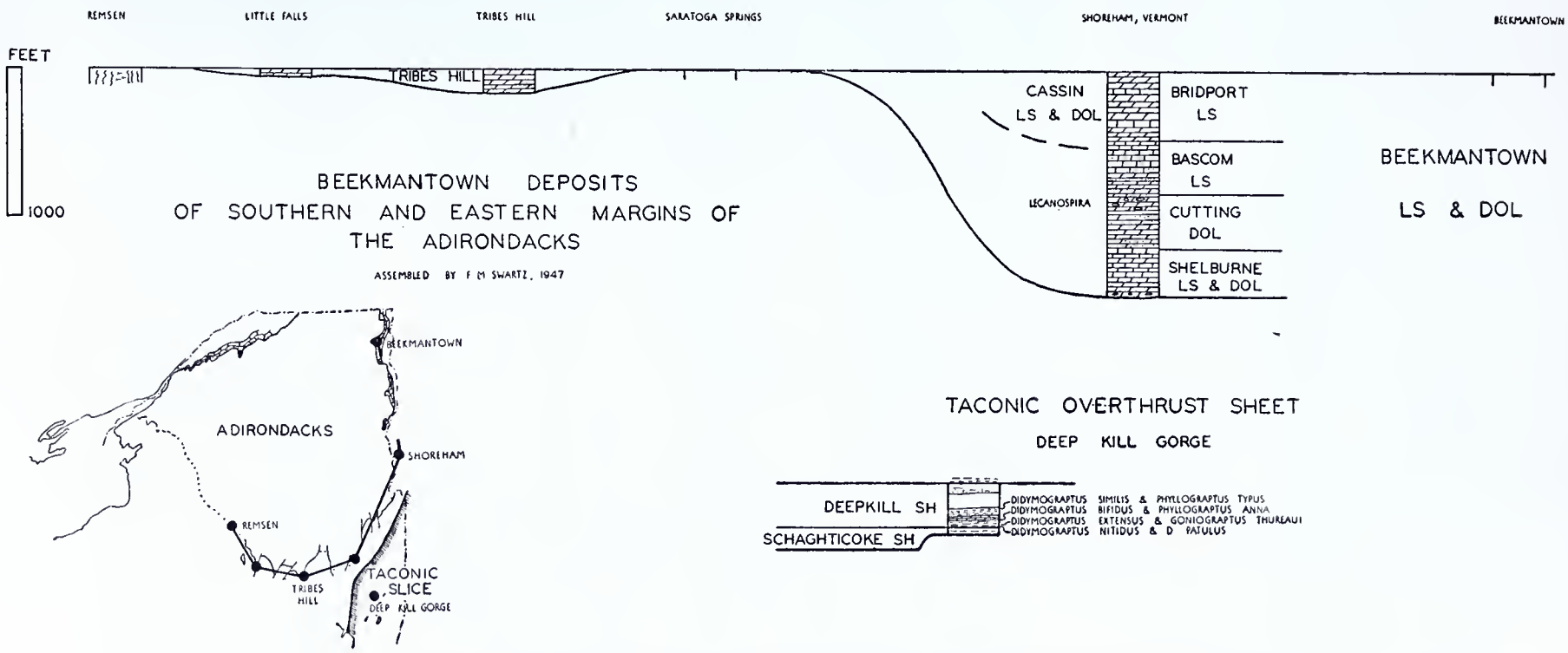


FIG. 18.—Stratigraphy of Lower Ordovician Beekmantown sediments along southern and eastern margins of Adirondacks and in Taconic plate.

West of Tribes Hill, the Tribes Hill limestone thins markedly in a short distance. It wedges out by unconformity between Little Falls and Remsen, and Beekmantown deposits are absent along the western margin of the Adirondacks at least as far north as Theresa.

The Tribes Hill limestone of the Tribes Hill region represents a thin feather edge of Beekmantown deposits lapping from the south onto the margin of the old Adirondack peninsula (Fig. 21).

BEEKMANTOWN DEPOSITS OF HUDSON RIVER VALLEY

Beekmantown deposits occur in the Hudson River Valley of eastern New York both in the allochthone of the Taconic plate, and in the autochthonous Wappinger terrane farther south.

The Wappinger terrane, exposed in small patches near the mid-length of the Hudson River Valley (Fig. 20), consists of approximately 1,000 feet of limestone containing Lower Cambrian, Upper Cambrian, Beekmantown, and Trenton fossil marine faunas. The Beekmantown part of the complex may be 500 feet thick, and may include most of the light gray, fine-textured limestones that constitute the prevailing lithologic facies of the Wappinger rocks. Complex deformation and poor exposures hinder detailed stratigraphic and structural interpretation of the Wappinger strata.

In the Taconic plate, north of Wappinger exposures, the Beekmantown and other deposits have been thrust westward from their more easterly region of original accumulation. The Beekmantown sediments of the overthrust mass or allochthone consist of the Schaghticoke shale and all but the topmost part of the Deepkill shale.

The Schaghticoke shale may be several times as thick as the exposed 50 feet of the type section. It contains the *Dictyonema flabelliforme* and *Staurograptus dichotomus* graptolite faunas, variously regarded as earliest Ordovician or latest Cambrian. The Schaghticoke rests with angular unconformity on the Lower Cambrian Schodack beds.

The Deepkill shales, above the Schaghticoke, are 200–300 feet thick, and consist of thin-bedded shaly limestones, thin-bedded grayish shales, and black clay shales rich in graptolites.

Five graptolite zonal faunas have been discovered in the Deepkill shale, and of these the four Beekmantown faunas are named in Figure 18.

The Schaghticoke and Deepkill were deposited well east of their present location. There has been some suggestion that they represent an easterly trough, distinct from the sedimentary trough in which the Beekmantown deposits at Shoreham were accumulated. It is plausible, however, that they represent clays carried from an easterly area of erosion into the eastern part of the same general trough represented by the sediments at Shoreham. Published data do not give clear evidence of a separated, eastern trough.

BEEKMANTOWN OF NITTANY VALLEY AND MORRISON COVE IN CENTRAL PENNSYLVANIA

The greatest thickness of Beekmantown sediments recognized in the New York-Pennsylvania region occurs in Nittany Valley, central Pennsylvania, near Bellefonte and State College. The sequence here consists of approximately 4,000 feet of carbonate rocks, three-fourths dolomite and one-fourth limestone. There are no significant beds of shale or even of shaly limestone. A single thin and local sandstone member occurs approximately 1,000 feet below the summit of the Beekmantown.

The formations of the Beekmantown of Nittany Valley are as follows (Fig. 19).

	Thickness (Feet)
Beekmantown group	
Bellefonte dolomite	
Medium-bedded, gray, dense dolomite or dolomitic limestone, weathering light-colored, dove gray to whitish. Presumably because of their finely crystalline texture, these dolomites are more closely jointed than are adjacent rocks, and opening of joints on weathered surface produces network of narrow clefts, suggestive of gashes made by sharp knife. Medium-textured grayish dolomite interlayers occur in subordinate quantity at some places. Near middle of formation is local, discontinuous sandstone member, ranging to 30 feet in thickness. Krynine (1940, 1941) reports grains of oölitic chert and heavy minerals, believed to come from erosion of locally upwarped areas of Mines and Gatesburg formations. Thickness of Bellefonte dolomite	1,900–2,100
Axemann limestone	
Medium-bedded, bluish limestone, some layers weathering with brownish, clayey bedding surfaces. Interbeds of dolomitic limestone are rare. Edgewise limestone conglomerates occur at some horizons. *Maclurites affinis*, *Hormotoma artemesia*, and species of *Bathyurus* and *Bolbocephalus* give evidence of equivalence with higher part of upper Beekmantown Bascom limestone of Vermont. Thickness	500
Nittany dolomite	
Thick- to medium-bedded, fairly coarse-textured, crystalline, steely gray dolomite, weathering much darker than Bellefonte formation, and lacking gashed weathered surfaces of that rock. One-inch vugs are common, and occur in well cores at depths of several hundred feet below surface as well as in outcropping ledges. Chert nodules, moderately common, are in part oölitic, the oölites generally smaller than in cherts of Mines formation. *Lecanospira compacta* of lower part of Bascom beds of Vermont Beekmantown, occurs in lower part of Nittany near Bellefonte. Thickness of Nittany dolomite	1,200
Stonehenge limestone	
Medium- to thick-bedded, finely crystalline, bluish, fairly pure limestone, with subordinate interbeds of dolomitic limestone; thin clayey films occur on some bedding surfaces. Edgewise limestone conglomerates at many levels. Asaphid trilobite, *Bellefontia collieana* abundant in upper 50–100 feet, with rare *Hystricurus* aff. *conicus*. *Ophileta complanata* at lower levels. Thickness	500– 600
Thickness of Beekmantown group approximately	4,000

Southward from Bellefonte and State College into the Tyrone Quadrangle and near Williamsburg at the northern entrance to Morrison Cove, the Beekmantown reportedly thins to 3,500 and to less than 3,000 feet. The Bellefonte and

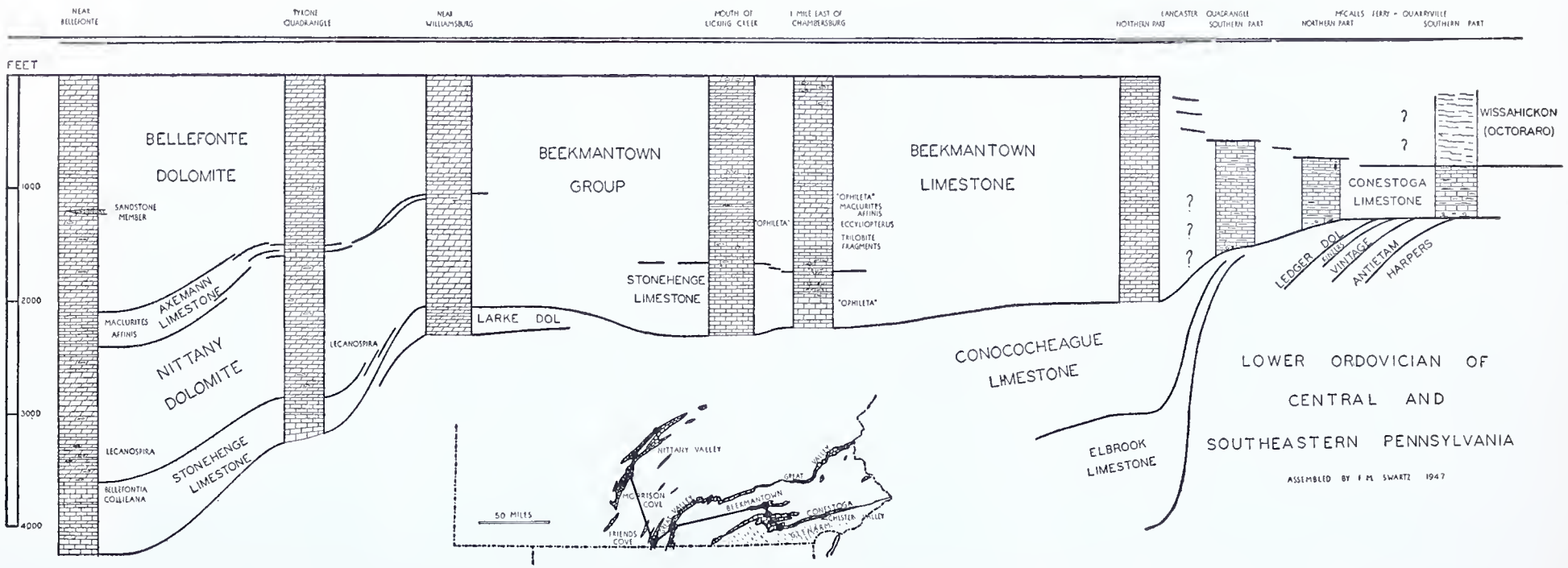


FIG. 19.—Stratigraphy of Lower Ordovician Beekmantown sediments from central Pennsylvania to south-central and southeastern Pennsylvania. True scale of convergence is shown by diagram at top of figure.

Nittany dolomites are persistent, but the Axeman and Stonehenge limestones thin, become irregular, and disappear. Much of the thinning of the limestone formations may result from lateral intergradation into dolomites of the Bellefonte and Nittany facies (Fig. 19).

The Nittany dolomite at Williamsburg, where the Stonehenge formation is missing at least as a limestone, is underlain by 250 feet of thick-bedded, rather coarsely textured Larke dolomite. Specimens of *Helicotoma uniangulata* have been identified by Butts among the rare Larke fossils. Although the original example of the gastropod is believed to have come from the Little Falls dolomite, Butts (1945) is inclined to consider it as evidence of Beekmantown age in terms of usages in the southern Appalachians and Missouri. The Larke in any event is latest Cambrian or earliest Ordovician in age.

BEEKMANTOWN OF GREAT VALLEY NEAR CHAMBERSBURG

In the Great Valley region near Chambersburg, Pennsylvania, and Hagerstown, Maryland, the Beekmantown deposits are approximately 2,400 feet thick, and consist of limestones and dolomites to virtual exclusion of other rock types.

Significant east-west changes occur in the Beekmantown within the Great Valley in the Chambersburg region. In the western part of the Valley, as near the mouth of Licking Creek (Fig. 19), the Beekmantown consists of about half magnesian limestone and dolomite, half purer limestone. The basal Stonehenge limestone member is an ill defined body of fairly pure limestone approximately 700 feet thick that contains little of the dolomitic limestone; in its upper part there are a few silty laminae and some dark limestone conglomerate with red limestone pebbles. There is a thin bed of coarse sandstone about 1,200 feet above the base of the Beekmantown, associated with scoriaceous black chert; some rosette-type cherts occur in the uppermost beds. In the eastern part of the Valley at Chambersburg, the dolomites and dolomitic limestones are reduced in volume, and form about a fourth instead of a half of the Beekmantown mass. The Stonehenge member at the base of the Beekmantown is here approximately 530 feet thick, with numerous silty laminae and thick beds of edgewise limestone conglomerate in its upper half.

The generalized section given by Bassler (1919) for the Beekmantown of the Chambersburg-Hagerstown region can be summarized as follows.

	Thickness (Feet)
Beekmantown limestone	
Fine-grained gray, finely laminated, interbedded limestone and magnesian limestone; in upper part there are some dense whitish cherts, quartzose cherts, and dolomite and limestone conglomerates	440
Turritoma acrea zone. Thin-bedded argillaceous and thick-bedded purer limestones. Many beds weather as though riddled by worm borings	200
Interbedded, dove gray limestone and gray laminated dolomitic limestone, with some limestone conglomerate; some sandy fossiliferous chert 75 feet above base	375
Ceratopea keithi zone, with *Hormotoma artemesia, Maclurites sordidus.* Blue and dove limestone; upper half cherty; at base is blue limestone with rounded quartz grains	250
Cryptozoön steeli, Maclurites affinis, Lecanospira compacta zone. Fine-textured limestone, with a few dolomitic beds. Lower 60 feet oölitic, somewhat cherty	550–650

	Thickness (Feet)
Stonehenge limestone member, containing *Ophileta complanata, Ecciliomphalus multiseptarious, Ribeiria nuculitiformis.* Upper limestones toward east have silty laminae, and beds of oölitic limestone and edgewise limestone conglomerate. Lower limestones are purer, weather whitish, and in part composed of finely brecciated limestone, the limestone fragments commonly less than 2 mm. in diameter	500–700
Thickness of Beekmantown limestone	2,400

The *Maclurites affinis*, *Lecanospira compacta*, and *Ophileta complanata* faunas are especially valuable for correlations with the Beekmantown of the Champlain region along the border of New York and Vermont.

BEEKMANTOWN IN PENNSYLVANIA EAST OF CHAMBERSBURG

East of Chambersburg, the recognized Beekmantown sediments crop out more or less continuously along the Great Valley into New Jersey, and are exposed in the limestone valleys near Lancaster and in Chester Valley.

Throughout the easterly part of the Great Valley, the Beekmantown rocks consist of limestones and dolomitic limestones that range from 1,000 to 2,000 feet in thickness; excepting that near Harrisburg some poorly preserved graptolites of seeming Beekmantown age occur in shales whose stratigraphy is not well understood.

Near Lancaster, in the northern half of the Lancaster Quadrangle (Fig. 19), the Beekmantown consists of nearly 2,000 feet of gray limestones and interbedded gray laminated dolomitic limestones and dolomites, containing some black chert.

Marked changes occur from the northern to the southern parts of the Lancaster Quadrangle. The 2,000 feet of Beekmantown limestone as known in the northern part of the quadrangle disappear in the southern part, and here instead there occurs the argillaceous Conestoga limestone that persists around the flanks of the Mine Ridge anticline and along Chester Valley with thicknesses of 500–1,000 feet. In the easterly part of Chester Valley, in the Honeybrook and Phoenixville quadrangles, the upper Conestoga consists of thin-bedded, blue to gray granular limestone with thin argillaceous partings; thin dark micaceous phyllites occur in the middle part; in the lower part there are thicker beds of pure granular or marble-like limestone, containing near their base some quartz grains and some limestone conglomerates.

The correlation of the Conestoga limestone is complicated not only by its lack of lithologic similarity with formations a short distance north; but also by the disappearance of the Beekmantown and Conococheague wherever the Conestoga is present, and by the uncertainties about relations of the Wissahickon schists that rest on the Conestoga along Chester Valley. Some poorly preserved fossils found in the Conestoga, however, have been identified with Beekmantown species and it appears to-day that the Conestoga limestone is in general a southeasterly Beekmantown facies, that received clays from a land area southeast of the Appalachian trough.

POSSIBLE BEEKMANTOWN OF GLENARM REGION

For reasons given in the general discussion of the Glenarm problem, it seems probable that the Cockeysville marble near Doe Run, Pennsylvania, is the southerly, somewhat more metamorphosed extension of the Conestoga limestone of adjacent Chester Valley (Fig. 5). In view of the argillaceous character of the Conestoga, and its marked thinning as compared with near-by Beekmantown limestones (Fig. 19), there is furthermore a distinct possibility that appreciable parts of the Wissahickon schists, where they rest on the Conestoga of Chester Valley (Figs. 5, 6), may likewise be equivalent to parts of the Beekmantown limestone.

The hypothesis of lateral change of the Beekmantown limestones, on the northwest, into the originally argillaceous and now phyllitic Conestoga plus some undetermined thickness of Wissahickon schist, is illustrated in Figure 21. This hypothesis of Beekmantown correlation seems reasonably plausible in terms of present knowledge. It carries one step farther the downward "migration" of the clay-limestone boundary that is observed from northwest to southeast in the Ordovician sediments of Pennsylvania, and that results in transformation of Trenton limestones of Nittany Valley into shales near Chambersburg, and possibly in change of the "Stones River" limestones near Chambersburg into Cocalico shale near Lancaster (Fig. 6).

REGIONAL RELATIONS, SEDIMENTATION, AND PALEOGEOGRAPHY OF BEEKMANTOWN DEPOSITS IN NEW YORK, PENNSYLVANIA, AND MARYLAND

Regional features of the Beekmantown sediments of New York, Pennsylvania, and Maryland are illustrated in the stratigraphic charts of Figures 18 and 19. The same data are reassembled and reinterpreted in the preliminary isopachous map of Figure 20, and paleogeographic map of Figure 21.

During Beekmantown sedimentation, seas spread over nearly all of the New York, Pennsylvania, Maryland area, with the principal exception of the Adirondack peninsula (Fig. 21). In the Lake Champlain Valley, and in central and much of southeastern Pennsylvania, flooding was relatively though probably not wholly continuous during Beekmantown time. Along the southern margin of the Adirondacks, however, only lower Beekmantown deposits are represented at the Beekmantown outcrop. The Ogdensburg limestone of the Thousand Islands region represents only later parts of the Beekmantown.

Throughout almost all of their exposures in the three states, the Beekmantown sediments predominantly are carbonate rocks (Figs. 18, 19).

In Pennsylvania, there is an over-all trend toward increase in proportion of dolomite on the west, and increase in limestone in comparison with dolomite toward the southeast. The Beekmantown deposits of Nittany Valley and Morrison Cove in central Pennsylvania include thick dolomite formations that contain almost no limestone interbeds and that compose three-quarters to almost the

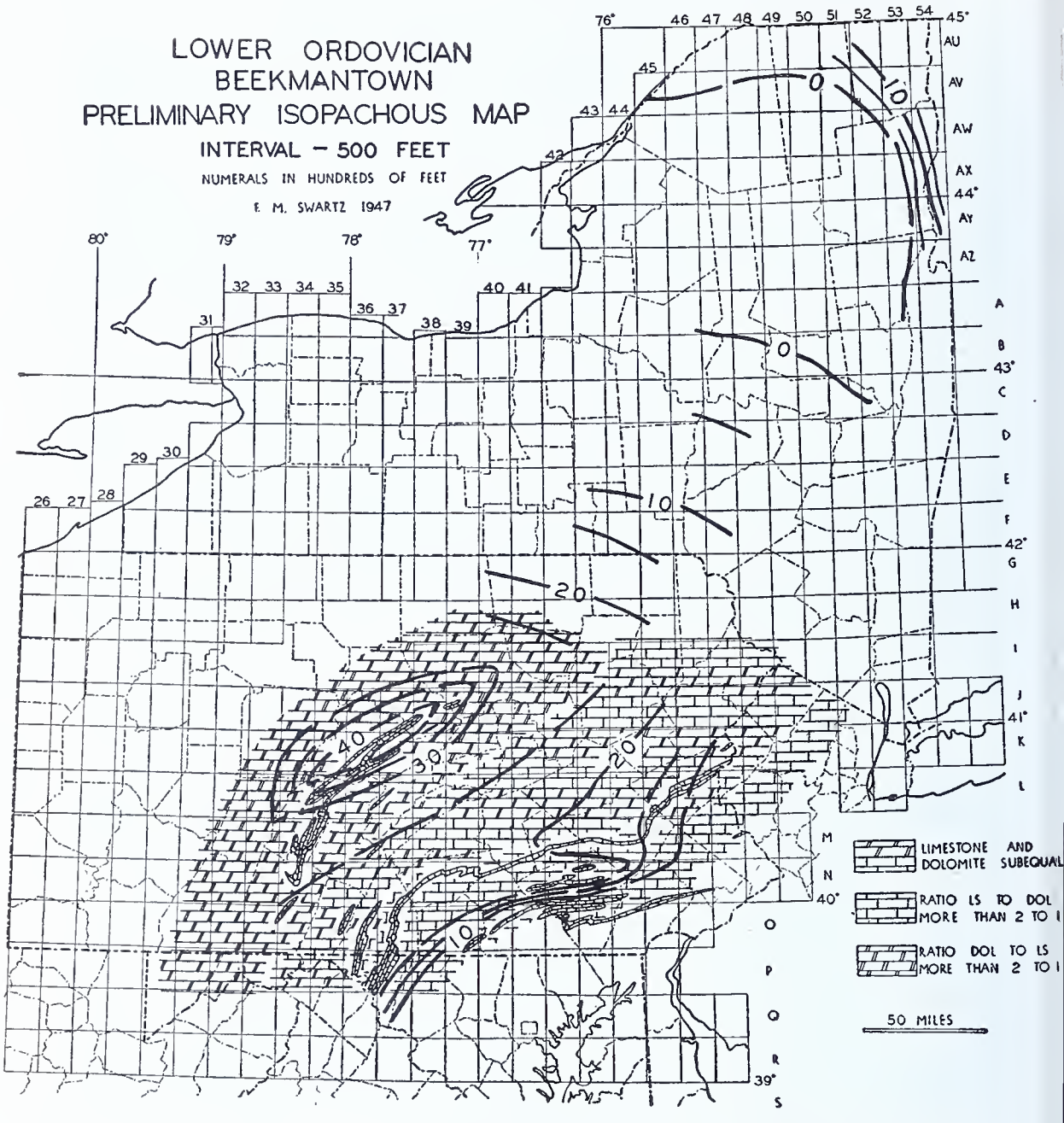

LOWER ORDOVICIAN
BEEKMANTOWN
PRELIMINARY ISOPACHOUS MAP
INTERVAL – 500 FEET
NUMERALS IN HUNDREDS OF FEET
F. M. SWARTZ 1947
LIMESTONE AND DOLOMITE SUBEQUAL
RATIO LS TO DOL MORE THAN 2 TO 1
RATIO DOL TO LS MORE THAN 2 TO 1
50 MILES

FIG. 20.—Preliminary isopachous map of Lower Ordovician Beekmantown sediments in New York, Pennsylvania, and Maryland.

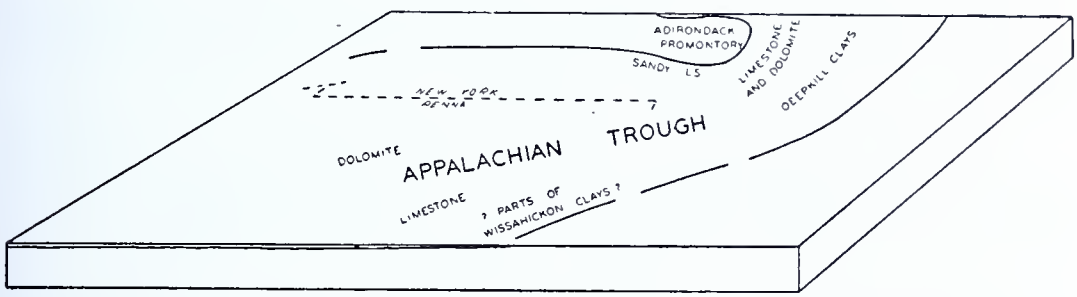
whole of the Beekmantown sequence. In these valleys the subordinate limestone formations thicken northeastward, thin and disappear southwestward. With further information, it may be found that the northeasterly increase of limestone is a component of the general easterly increase.

On the western side of the Great Valley near Chambersburg, south-central Pennsylvania, the Beekmantown sediments consist of interbedded limestones

and dolomites, nearly equal in amount. On the eastern side of the valley, there is appreciable diminution in proportion of dolomite, the dolomitic interbeds forming about a fourth of the Beekmantown succession.

Through the Great Valley regions of eastern Pennsylvania, and in the limestone valleys near Lancaster, the Beekmantown strata consist of limestones and interbedded dolomitic limestones and dolomites, without clearly understood trends. Descriptions of the argillaceous Conestoga limestone of Chester Valley suggest that dolomites are subordinate.

The thin wedge-edge of Tribes Hill lapping onto the southern margin of the Adirondacks includes limestones and some dolomitic limestones. The Beekman-



PLAUSIBLE PALEOGEOGRAPHY OF BEEKMANTOWN SEDIMENTATION. THE DOLOMITE FACIES MAY MARK THE MORE OPEN, SALINE PART OF THE SHALLOW APPALACHIAN SEAWAY. SMALL QUANTITIES OF SAND WERE CARRIED FROM THE LOW-LYING ADIRONDACK PROMONTORY INTO NEIGHBORING WATERS, WHICH RETREATED SOMEWHAT IN LATER BEEKMANTOWN TIME. THIN, GRAPTOLITIC DEEPKILL CLAYS, DERIVED FROM AN EASTERLY LAND SURFACE, ACCUMULATED SLOWLY IN THE ORIGINAL SITE OF THE TACONIC PLATE. PARTS OF THE WISSAHICKON CLAYS MAY LIKEWISE HAVE BEEN DEPOSITED DURING BEEKMANTOWN TIME

FIG. 21.—Plausible paleogeography of Lower Ordovician Beekmantown sedimentation in New York, Pennsylvania, and Maryland.

town sediments of the Champlain region east of the Adirondacks consist of subequal parts of limestones and of dolomitic limestones and dolomites.

Non-carbonate elements form a small percentage of the Beekmantown rock materials of the region. In part these were derived from western erosion surfaces, in part from easterly erosion surfaces; some parts may have come from local uplifts within the general region of flooding; the minor cherts and presumably part of other insoluble constituents of the carbonates were precipitated from solution.

The Tribes Hill limestone of the southern margin of the Adirondacks contains a moderate proportion of quartz sand. There are subordinate sandy dolomites and limestones and some thin sandstones in the Lake Champlain region east of the Adirondacks, but the total amount of sand probably does not constitute more than 5 per cent of the rock mass. One thin sandstone member ranging to 30 or 40 feet in thickness, occurs locally in the upper part of the 4,000 feet of Beekmantown dolomites in Nittany Valley, central Pennsylvania. Limestones, 300–550 feet above the base of the Beekmantown near Chambersburg, Pennsylvania, contain thin silty laminae.

The Beekmantown group is represented in the Taconic plate near Albany, New York, by approximately 500 feet of clayey to silty shales, originally deposited in a more easterly position. In and near Chester Valley in southeastern Pennsylvania, the Conestoga limestone of Beekmantown age contains much argillaceous material. It appears plausible that part of the Wissahickon schist, where it rests on the Conestoga, may represent clays of Beekmantown age (Figs. 7, 21).

The Beekmantown limestones and dolomites generally are not pure enough to be used for chemical purposes. Small percentages of clayey substances may account for part of the impurities, but part should be material deposited from solution.

Cherts occur in parts of the Beekmantown in various regions, but in terms of volume of rock are always very subordinate. Some of the cherts of the Nittany dolomite of central Pennsylvania are oölitic.

The distribution of sands in the Beekmantown sediments of the eastern and southern margins of the Adirondacks strongly indicates that they were derived from the Adirondack peninsula of Beekmantown time. The small volume of sands in the Beekmantown adjacent to the Adirondacks indicates that the Adirondack peninsula was however low and not undergoing rapid erosion. Much of these sands may have been furnished by minor reworking of the Potsdam sediments. The peninsula did not furnish enough clay to give rise to any significant deposits of clay or even of distinctly clayey sands or carbonates.

Grains of oölitic chert in the local sandstone member of the Beekmantown dolomite of Nittany Valley suggest erosion of locally upwarped parts of the Nittany or Mines formations in some reasonably near-by region.

The Beekmantown clays of the Taconic plate near Albany evidently were deposited in the easterly part of the Appalachian trough, and were derived from erosion of an easterly land surface. The clayey materials of the Conestoga limestone of Chester Valley, and the clays of any Beekmantown parts of the Wissahickon, must likewise have come from land surfaces southeast of the trough. The silty laminae of the upper part of the Beekmantown near Chambersburg also came from a source on their east. It is by no means certain, however that these easterly areas of erosion were parts of a single surface of erosion, in the manner illustrated in Figure 21. Instead, the easterly lands of Beekmantown time may have been sufficiently submerged so that there were several large islands. Whatever the exact configuration of the areas of erosion, they were moderate in relief and did not supply a great flood of detritus to the Beekmantown seas.

The silts of the upper part of the Stonehenge near Chambersburg as well as minor sands at higher levels in the Beekmantown, may have been furnished by erosion of a locally elevated part of the sea floor, rather than from the more easterly region that provided the clays of the Conestoga and Wissahickon.

The axis of maximum thickness of known Beekmantown sediments traverses central Pennsylvania and trends northeastward toward the Champlain region

in the manner indicated in Figure 20. The greatest thicknesses of approximately 4,000 feet are found in Nittany Valley. Because of the limited outcrops in comparison with the total area of the three states, only broad features of thickness changes can be pictured in Figure 20.

Shallow-water marine snails, brachiopods, and trilobites are known at many levels in the Beekmantown sediments. Remains of planktonic graptolites occur in dark shales of the Taconic plate, possibly deposited at moderate depths, and a few graptolites have been found in some of the Beekmantown limestones. General rarity of shelly faunas in the dolomitic strata may be due to the dolomitization itself. In southeastern Pennsylvania, recrystallization may cause the lack of known fossils in the Wissahickon. Fossils are rare and poorly preserved in the deformed and partially recrystallized Conestoga limestone. Mechanical fragmentation and solution during sedimentation of course took their toll of shells in all the sediments, especially where wave agitation and currents are more active.

The known Beekmantown sediments of New York, Pennsylvania, and Maryland are for the most part clearly marine. No demonstrably continental or even estuarine deposits have been recognized.

In summary, it appears that during Beekmantown time shallow, marine waters flooded much of the area of New York, Pennsylvania, and Maryland. The northeastward continuation across the Champlain region was constricted by the eastwardly jutting Adirondack peninsula. It is probable that oceanic connections both northeast and southwest helped maintain the marine salinities of the time throughout most of the trough region.

The adjacent land areas were low, and furnished relatively little clastic sediment to the trough. Small quantities of sand were carried from the Adirondack peninsula into adjacent waters. Easterly parts of the Appalachian trough received some clay and silt from lands east of the trough, that may have had the form of an island arc.

General shallowness of water is attested by the beds or lenses of edgewise limestone conglomerates that are fairly numerous in some of the limestone members in central and southern Pennsylvania, by limestone oölites and siliceous oölites where these are present, and by the general characters of the shelly faunas.

In the Pennsylvania region, there is regional increase of dolomites toward the east. The relation of dolomites and limestones to bedding strongly supports the view that dolomitization kept close pace with sedimentation.

Within the regions of sedimentation, gentle and slightly discontinuous subsidence was the over-all tectonic pattern, so that slow downwarping was nearly balanced by sedimentary upbuilding of the surface of deposition. Gentle warping occurred along the margins of the Adirondacks and produced significant fluctuations in borders of the area of deposition. Some erosion of locally upwarped areas within the general region of flooding may have occurred in central and southern Pennsylvania.

Middle Ordovician Chazyan Deposits

Outcrop areas of Chazyan in New York, Pennsylvania, and Maryland

The Middle Ordovician Chazyan limestone was named by Emmons (1842) from Chazy Village near Plattsburg in the northeastern corner of New York state. The distribution of the Chazyan in terms of the outcrop belts in New York differs markedly from that of succeeding parts of the Middle Ordovician, since the Chazyan is wanting along the southern and western margins of the Adirondacks, where Black River and Trenton deposits are extensively developed. Furthermore, the Chazyan is represented by thick limestones along the eastern margin of the Adirondacks, whereas Black River deposits and limestones of Trenton age are thin, and local in development.

The distribution and characters of the Chazyan are discussed under the following headings.

Chazyan of Lake Champlain region in New York and Vermont
Chazyan relations along southern and western flanks of Adirondacks
Chazyan of Hudson River Valley
Chazyan of Nittany Valley and Morrison Cove in central Pennsylvania
Chazyan of Great Valley near Chambersburg
Chazyan in southeastern Pennsylvania east of Chambersburg
Regional relations, sedimentation, and paleogeography of Chazyan deposits in New York, Pennsylvania and Maryland

Chazyan of Lake Champlain region in New York and Vermont

The Chazyan limestones were named from Chazy Village about 10 miles north of Plattsburg in northeastern New York. Better exposures are, however, found on Valcour Island approximately 5 miles south of Plattsburg, where the Chazyan was divided by Brainerd and Seely (1888; Brainerd, 1891) into parts A, B, and C, given in ascending order. These members were respectively named the Day Point limestone, Crown Point limestone, and Valcour limestone by Cushing (1905). The Valcour Island section can be summarized as follows.

	Thickness (Feet)
Chazyan group	
Valcour limestone	
Tough arenaceous magnesian limestone, passing to sandstone	17
Dark impure limestone	125
Dove-colored limestone	60
Thickness of Valcour limestone	202
Crown Point limestone	
Bluish black limestone. *Maclurites magna*	75
Dark compact limestone	20
Bluish black limestone, nodular. *Maclurites magna*	210
Gray, thick-bedded limestone, crinoidal	20
Impure nodular limestone. *Maclurites magna*	25
Thickness of Crown Point limestone	350

	Thickness (Feet)
Day Point limestone	
Gray limestone	90
Dark bluish gray limestone. *"Orthis" costalis* (aa)	110
Slaty sandstone grading to slate and nodular limestone	82
Gray or drab sandstone and shale	56
Thickness of Day Point limestone	338
Thickness of Chazyan group	890

The Chazyan sediments near the northern end of Lake Champlain thus consist of approximately 900 feet of limestone, with 140 feet of sandy shale or slate and some limestone at the base, and 17 feet of sandy magnesian limestone at the top. The middle part contains the especially distinctive species, *Maclurites magna*. *"Orthis" costalis* characterizes part of the lower member, and *"Camarotoechia" plena* is found in the upper member. Various early cephalopods occur in each of the divisions of the Chazyan, and brachiopods, gastropods, and trilobites are abundant in some layers.

Chazyan limestones persist southward from Valcour Island through the Lake Champlain region into the marble belt of southern Vermont where they provide some of the marble rocks of the Rutland region. Traced northward, the Day Point member disappears near Shoreham, Vermont, and the sediments undergo various local changes in thickness and facies. In general, the Chazyan sediments dominantly are limestones or marbles through the Lake Champlain region. Some minor sands and clays seem to have been derived from the Adirondack region on the west. Subordinate clastics of sandy and silty limestones of the Valcour limestone near Middlebury, Vermont, appear to have been derived from erosion surfaces east of their area of deposition, possibly from locally upwarped Cambrian sediments.

Southwestward from Shoreham and Rutland, Vermont, the Chazyan sediments disappear beneath the Taconic plate, which obscures their autochthonous characters in the Albany region.

CHAZYAN RELATIONS ALONG SOUTHERN AND WESTERN FLANKS OF ADIRONDACKS

Chazyan sediments are absent throughout the outcrops along the southern and western flanks of the Adirondacks. The thin Pamelia limestone of the Watertown-Lowville region in the Black River Valley west of the Adirondacks has been referred to the Stones River or Chazyan by some geologists, but is classed as Black River by Kay.

The complete absence of Chazyan deposits along the outcrop lines south and west of the Adirondacks suggests that those belts were emergent during Chazyan time, rather than that Chazyan sediments were deposited and then removed by erosion. It thus appears that the margin of the Adirondack emergent surface lay farther south during Chazyan time than had been true during the preceding Beekmantown stage (compare Fig. 20).

CHAZYAN OF THE HUDSON RIVER VALLEY

Chazyan sediments occur in the overthrust masses of the Taconic plate in the middle to northern parts of the Hudson River Valley. It is not now clear to what extent they are represented in the autochthonous Wappinger limestone terrane at mid-length of the Hudson River Valley south of the Taconic plate.

Chazyan sediments are represented in the Taconic plate by the uppermost few feet of the Deepkill shale plus much of the Normanskill shale.

The Normanskill shales are probably 2,000 feet thick. Prevailingly, these shales are dark gray to black. There are some red and green shale horizons, some silty to sandy shales, and some white-weathering cherts.

Two graptolite zones, each with a large and cosmopolitan suite of graptolites, have been recognized in the Normanskill deposits. The lower zone is characterized especially by *Nemagraptus gracilis*, the upper by *Corynoides gracilis*. The *Nemagraptus gracilis* zone has been considered Chazyan by Ruedemann, whereas he has classed the *Corynoides gracilis* beds with the Black River.

If the structure of the Taconic plate has been properly interpreted by Keith and by Prindle and Knopf (1932), the Normanskill shales and associated sediments of the plate were deposited east of the Chazyan marbles near Rutland, now at the eastern margin of the plate. According to this view, the Normanskill clays were deposited in the eastern part of the Chazyan basin, and came from land surfaces east of the basin.

CHAZYAN OF NITTANY VALLEY AND MORRISON COVE IN CENTRAL PENNSYLVANIA

The Middle Ordovician formations of Nittany Valley and Morrison Cove, central Pennsylvania, described by Charles Butts (1936, 1939, 1945), in his invaluable quadrangle reports, have been reinvestigated by Kay (1944, 1947). Kay's correlations, pending possible modifications after further faunal studies, restrict the Chazyan to the earliest parts of the strata that were so classed by Butts.

In the Bellefonte region (Fig. 23), the Hatter and Benner limestones of Kay, and at some places the Nealmont as well, were included in the Carlim limestone by Butts and referred to the Chazyan. This correlation was based chiefly on large specimens of *Maclurites* that were identified with the Chazyan *M. magna*, whereas Kay believes that they represent other species of the genus.

According to Kay's latest classifications, the Chazyan is represented in the Nittany Valley-Morrison Cove region only by the "Loysburg" limestone, possibly 50–100 feet in thickness. Work on the "Loysburg" has been incidental to Kay's studies of the overlying strata, and neither the stratigraphy of the formation nor its relations to the subjacent Beekmantown are as yet well understood. The strata tentatively classed as Loysburg are impure limestones with some interbeds of dolomite. Some beds have a peculiar lamination leading to the name "tiger-stripe" beds.

At their base, the "Loysburg" strata may be transitional with the Bellefonte dolomite. At their summit, they are believed by Kay to be disconformably overlain by the Hatter limestone of the Black River group.

CHAZYAN OF GREAT VALLEY NEAR CHAMBERSBURG

The Chazyan Stones River limestone, as described by Stose (1909) and Bassler (1919) in the Great Valley region near Chambersburg, Pennsylvania, and Hagerstown, Maryland, is 1,000–1,100 feet thick and consists of interbedded pure and magnesian limestones.

The general succession of these Stones River strata follows.

	Thickness (Feet)
Thick-bedded and some thin-bedded dense to finely crystalline, mostly pure and dove-colored limestones. Small, four-sided, tubular coral, *Tetradium syringoporoides* occurs in some beds	300
Thick-bedded, finely crystalline, dove-colored limestone, with interbeds of dark, medium textured limestones, and finely textured fossiliferous and oölitic limestones, in part having numerous bands of black chert. *Maclurites magnus* fauna, with *Tetradium syringoporoides*, orthid brachiopods, *Bucania*, *Ampyx*, *Eoleperditia*	200
Thick-bedded and thin-bedded, finely crystalline, in part dove-colored and pure limestone, interbedded especially in lower part with dolomitic limestones. Edgewise limestone conglomerates rare	600

The upper beds especially of the Stones River limestone include the purest limestones of the Chambersburg-Hagerstown region, and are extensively quarried.

CHAZYAN IN SOUTHEASTERN PENNSYLVANIA EAST OF CHAMBERSBURG

The Chazyan Stones River limestone extends northeastward from Chambersburg along the Great Valley to and beyond Harrisburg; Cocalico shale of Chazyan or younger age occurs in a small area 30 miles southeast of Harrisburg; if the Glenarm series in southeastern Pennsylvania is Paleozoic in age it may also include Chazyan equivalents originally deposited as clays.

The Stones River of the Great Valley is first described, and possible Chazyan relations farther southeast are briefly considered.

Traced northwestward along the Great Valley in Pennsylvania, the Stones River limestone beds gradually diminish from about 1,100 feet near Chambersburg, to 300 feet where their belt of outcrop crosses the Susquehanna in the southern outskirts of Harrisburg. In part, at least, the thinning is supposed to be due to disappearance of some of the basal part of the formation. As a whole, the Stones River beds persist through this belt as relatively pure, thin- to thick-bedded limestones.

East of Harrisburg, the Stones River is thought to be represented by pure, white sugary marbles and fine-grained blue limestones, that have been opened in numerous quarries along a narrow belt of outcrop between Hummelstown and Lebanon. The easternmost known occurrence of these Stones River strata is at Womelsdorf, 35 miles east-northeast of Harrisburg, where a specimen of *Maclurites* cf. *magna* was discovered in them. No Chazyan sediments have been

recognized farther east in the Great Valley between this place and the Jutland area in New Jersey, 10 miles beyond the Pennsylvania line, where some questionable Chazyan or Normanskill graptolites have been reported in shales of Martinsburg type.

Although there are 300 feet of Stones River limestones in the belt of outcrop extending through Harrisburg, the formation is generally though perhaps not everywhere absent along a parallel synclinal belt extending through Steelton, 2–4 miles farther south (Stose and Jonas, 1939, Fig. 4, p. 81). In the Steelton syncline the Beekmantown is for the most part overlain directly by the Martinsburg shale, or by shaly limestones classed as Leesport and thought to be early Trenton in age. At only a few places have pure limestones of Stones River type been discovered at the junction of the Beekmantown and Leesport strata.

At some localities where the Beekmantown and Martinsburg are in contact along the Steelton syncline, there is good evidence that the boundary is unconformable, and that the Beekmantown underwent emergence and some erosion before the beginning of Martinsburg sedimentation.[5]

The Cocalico shale is known by this name only along a 24-mile belt centering about 30 miles east-southeast of Harrisburg. The formation rests on Beekmantown limestone, and is perhaps 1,000 feet thick, with its summit everywhere truncated by the present level of erosion, so that relations to overlying sediments are not directly established. Poorly preserved graptolites found in 1921 and 1923 were provisionally identified by Ulrich with Normanskill or Chazyan species. Doubt, however, has been thrown on this interpretation of age because the lower part of the Cocalico contains purple and greenish shales and greenish sandstones similar to beds found farther north in basal Martinsburg strata of supposed Trenton age.

The Conestoga limestone farther southeast in the Chester Valley region, was for a time thought probably to be Chazyan in age. The latest fossil discoveries indicate that in part at least it is a Beekmantown equivalent. It is probable that if Chazyan sediments are present in the Chester Valley region they occur within the clayey rocks that have been transformed by metamorphism into Wissahickon schist.

REGIONAL RELATIONS, SEDIMENTATION, AND PALEOGEOGRAPHY OF CHAZYAN DEPOSITS IN NEW YORK, PENNSYLVANIA, AND MARYLAND

In the New York, Pennsylvania region, Chazyan sediments are represented by a more northerly maximum of limestone deposits located along the eastern flank of the Adirondacks in northeastern New York and Vermont; and in the south by another limestone maximum in the Chambersburg-Hagerstown region where the Great Valley crosses the boundary of Pennsylvania and Maryland (Figs. 22, 26). It is possible though not well assured that the limestones of these two main areas of accumulation represent the axial region of a continuous limestone belt that ex-

[5] Graptolites of seeming Chazyan and Beelmantown age are found in some Martinsburg-type shales near Steelton. The occurrences raise stratigraphic-paleogeographic-tectonic questions not satisfactorily answered (Stose, 1946).

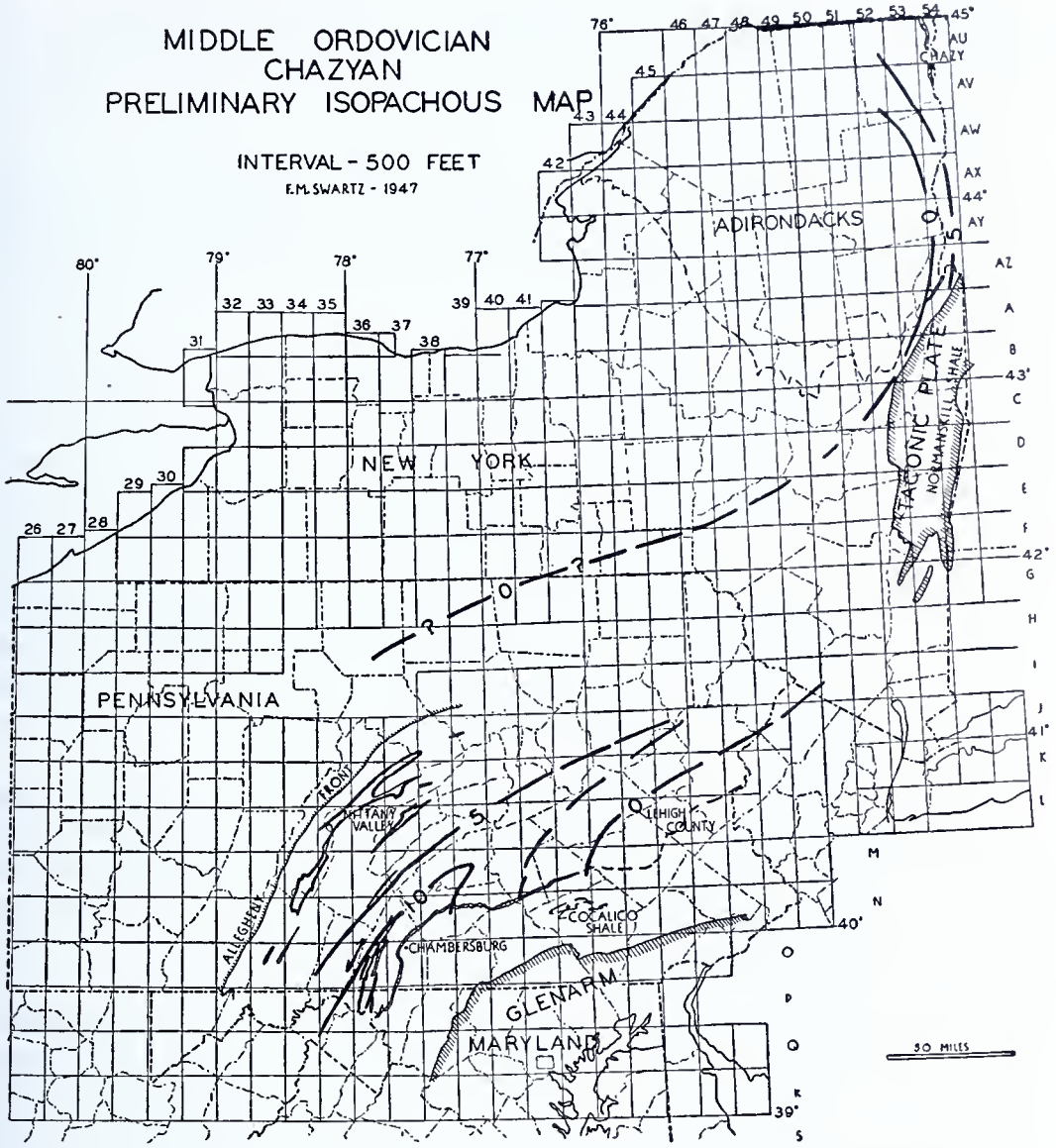


FIG. 22.—Preliminary isopachous map for Middle Ordovician Chazyan sediments in New York, Pennsylvania, and Maryland.

tends southwestward from the type Chazyan area east of the Adirondacks, being covered by the allochthonous Taconic plate in the Hudson Valley region near Albany, New York, and then overlain by thick autochthonous Paleozoic sediments as it extends below ground through the Catskill Mountain region of New York and through the northeastern part of Pennsylvania. Future faunal studies may help both to establish more clearly the degree of equivalence of the limestones of the two areas, and to indicate the ease, or on the other hand difficulty, of intermigration of the creatures of the ancient sea floors.

In both the northern and southern areas, the limestones seem to thin toward the west without known significant development of land-derived clastic sedi-

ments. Especially in the north, clays deposited southeast of the limestone belt give evidence of lands bordering the eastern margins of the basins. So far as evidence is available, the known Chazyan sediments of the region were deposited under marine or brackish rather than fresh-water conditions.

In New York, Chazyan sediments are wanting along the southern and western flanks of the Adirondacks. It is not known that Chazyan deposits occur at depth in New York west of the Adirondack region, although sediments of the age may cross the southeastern part of the state in the manner provisionally suggested in Figures 22, 26.

The Normanskill shales of the Albany region of New York are largely, it is believed, Chazyan in age; but current interpretations suggest that their present location is the result of Taconic overthrusting and that they represent clays originally deposited east of Chazyan marbles quarried in southern Vermont east of the present Normanskill area. Paleogeographically, according to this structural interpretation, lands east of the Chazyan trough were sufficiently elevated to send large volumes of clay and some sand into the eastern reaches of the Chazyan seas.

In the south, the Chazyan Stones River limestones, 1,100 feet thick near Chambersburg, seem to thin out northwestward; at least, the recognized Chazyan or Loysburg limestones of Nittany Valley in central Pennsylvania are only 50–300 feet thick. Eventually, it may be found that some subjacent dolomitic beds are Chazyan in age rather than Beekmantown as is now supposed.

Chazyan sediments are absent in the Great Valley in the Lehigh County region of eastern Pennsylvania. It is not now clear whether this is the result principally of post-Chazyan and pre-Trenton erosion of a Chazyan blanket of sediments, of non-deposition on a promontory projecting from the eastern land areas that bordered the Chazyan trough, or perhaps of non-deposition on a large island-belt that partly separated the trough of limestone deposition, on its northwestern flank, from a southeastern trough partly floored with clayey sediments.

East of Lehigh County, near Jutland in New Jersey, there are shales of possible Normanskill or Chazyan age. Likewise, southwest of Lehigh County, the Cocalico shales may be Chazyan in age, at least in part. If the Glenarm metasediments of southeastern Pennsylvania are Paleozoic in age, they also could include representatives of additional clays and silts deposited during Chazyan time.

Middle Ordovician Black River and Trenton Deposits

Naming of Black River and Trenton, and distribution of outcrops in New York, Pennsylvania, and Maryland

The Middle Ordovician Black River limestone group was named by Vanuxem in 1842 from outcrops along the valley of the Black River on the western flank of the Adirondack Mountains in New York. The "Blue Foetid Limestones and Shales of Trenton Falls" had earlier been described by Conrad in 1837 from the falls of that name on West Canada Creek in the headwater region of the Mohawk Valley, northeast of Utica, New York.

The Black River and Trenton sediments of New York have been studied by many geologists. The earlier stratigraphic versions of Conrad, Vanuxem, Hall, and other workers were reinterpreted during the early decades of the present century by Ruedemann (1901, 1908, 1912, 1925, 1935), whose studies have been especially significant in establishing faunal zones and thus the age and facies relationships of the laterally varying limestone and shale sediments. More recently Kay (1937, 1944) has presented detailed correlations and facies and paleogeographic interpretations of the Black River and Trenton in New York, and has also discussed the equivalent strata in central Pennsylvania.

Major features of the Black River and Trenton sediments in each of the important belts of outcrop in New York, Pennsylvania, and Maryland are summarized under the following headings.

Black River and Trenton of Black River Valley
Black River and Trenton of Mohawk Valley
Black River and Trenton of Hudson Valley
Black River and Trenton of Nittany Valley and Morrison Cove in central Pennsylvania
Black River and Trenton of Great Valley near Chambersburg
Black River and Trenton of Great Valley northeast of Chambersburg
Possible relations of Black River and Trenton southeast of Great Valley
Regional relations, sedimentation, and paleogeography of Black River and Trenton deposits in New York, Pennsylvania, and Maryland

BLACK RIVER AND TRENTON OF BLACK RIVER VALLEY

In the valley of the Black River near Watertown, New York, on the western flank of the Adirondacks, the Black River limestones are 200 feet thick (Fig. 23), and for some distance south rest directly on the crystalline rocks of the Adirondack pre-Cambrian complex. The lower, somewhat impure Pamelia limestone is overlain by 50–60 feet of dove-colored Lowville limestone, long called "Birdseye limestone" because weathered surfaces are spotted by cross sections of the small, calcite-filled worm tubes, *Phytopsis tubulosum*. The small, four-sided prisms of the coral, *Tetradium cellulosum* are locally profuse, and intercalated oölitic and some shaly layers contain orthocerids, trilobites, and *Eoleperditia*. At the top of the Black River group are thin, cherty Leray limestone and Watertown limestone, combined as Chaumont limestone by Kay. The Watertown is characterized by *Gonioceras anceps* and other nautiloids.

Above the Black River strata near Watertown there are in turn another 300–350 feet of more argillaceous and less resistant limestones of the Trenton group, and with these Kay has grouped an overlying 150 feet of shales that are black below, gray and silty above.

The Sherman Fall beds, forming the median 200 feet of the Trenton limestones are more shaly than the lower Trenton limestones; above them likewise are heavier-bedded limestones, overlain by 25–50 feet of shaly limestone transitional with the overlying shale sequence.

A half-inch, discontinuous layer of altered volcanic ash or metabentonite occurs in the lower Trenton Rockland beds of the Watertown area.

Some bedding surfaces of the Trenton limestones bear large-scale ripple-marks with wave-lengths of 2–3 feet. The ridges generally anastamose. They may

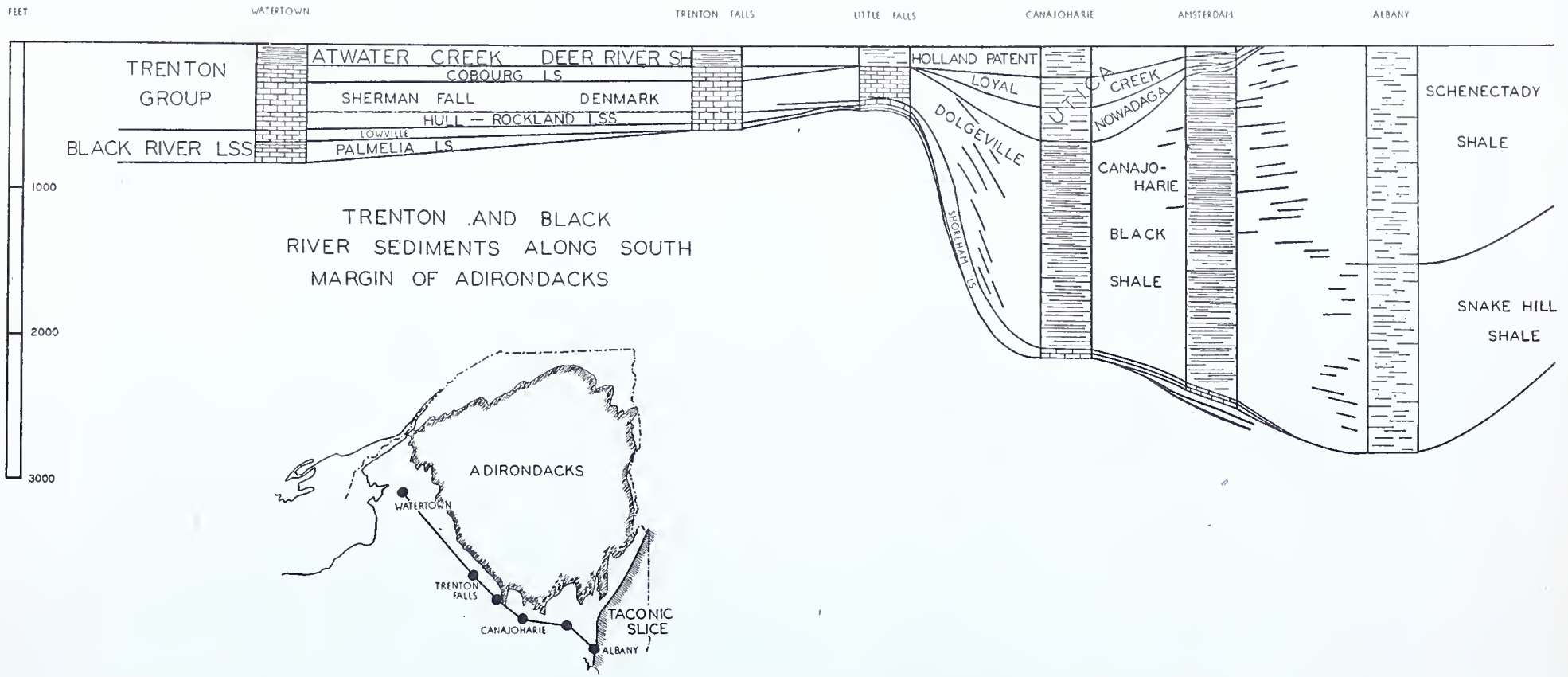


FIG. 23.—Stratigraphy of Middle Ordovician Black River and Trenton sediments in New York along western and southern margins of Adirondacks. (Modified from Kay)

have resulted from storm waves affecting the bottom sediments in fairly shallow but open stretches of the sea; their trends in direction suggest that the storm winds prevailingly came either from the northeast or southwest.

The Trenton strata contain a succession of zonal faunas. In the lowest Trenton Rockland beds are found the gastropods, *Maclurites logani* and *Phragmolites compressus*, together with *Triplecia cuspidata* and other brachiopods, and some significant trilobites and cephalopods. The trilobites, *Encrinurus cybeleformis* and *Hemiarges paulianus*, are important in the Hull limestone. The Sherman Fall limestones contain in their lower third the well known Trenton bryozoan, *Prasopora simulatrix* and the distinctive trilobite, *Cryptolithus tesselatus*. The overlying Cobourg limestone is characterized by the brachiopod, *Rafinesquina deltoidea*. The Deer River and Atwater Creek shales, included at the summit of the Trenton by Kay, are characterized by several of the graptolite zones established by Ruedemann, as well as by the trilobites *Triarthus eatoni* and *Ogygites latimarginatus*.

The sediments are shallow-water, marine deposits, formed in waters generally abounding in marine life. The Trenton limestones especially are characterized by petroliferous odors.

BLACK RIVER AND TRENTON OF MOHAWK VALLEY

The Black River and Trenton strata continue without great change along the southwestern flank of the Adirondacks from Watertown to the vicinity of Trenton Falls in the western part of the Mohawk Valley (Fig. 23). The early Black River Pamelia limestone disappears by unconformity, but the Lowville limestone is persistent. The shaly Sherman Fall limestones are the beds mainly exposed at Trenton Falls. Most geologists working in the Trenton Falls area have drawn the summit of the Trenton at the limestone-shale boundary marking the summit of the Cobourg limestone, rather than within the overlying shales as is done by Kay.

Many of the members of the Black River and Trenton groups of the Watertown-Trenton Falls region are separated by inconspicuous disconformities. Fluctuations of the platform of deposition were sufficient to cause transgressions and regressions of the sea waters, but the emergences were gentle and were not accompanied by pronounced warping or deep erosion.

Marked changes take place in the Black River and Trenton sediments as they are traced from Trenton Falls eastward along the Mohawk Valley (Fig. 23). The sequence thins near Little Falls, with disappearance by disconformity of the Black River and early Trenton, as well as of the later Trenton Cobourg limestone.

East of Little Falls the sediments expand markedly and undergo marked changes in lithologic and faunal characters. Shales and somewhat silty shales supposed to correspond in age with the Cobourg limestone and overlying shales at Trenton Falls and farther northwest, are questionably classed as Utica shale. The Sherman Fall limestones first pass into the very argillaceous Dolgeville lime-

stone and, with further increase in clay and decrease in lime, become the graptolitic Canajoharie black shale of the eastern part of the Mohawk Valley. Continuing eastward, the upper beds of the Canajoharie become silty and grayish as they begin to pass into the Schenectady shale. Only the lowest beds of the Sherman Fall, and locally parts of the early Trenton and Black River, continue as limestones into the eastern part of the Mohawk Valley.

Several thin metabentonites occur in the Canajoharie shale and in the underlying Trenton limestones of the eastern part of the Mohawk Valley.

The Canajoharie shales are largely black, clay shales in the lower half, interbedded black and gray, silty shales above. Ruedemann established five graptolite zones in the Canajoharie, that have been especially valuable in correlation of these strata. He further discovered that the graptolites of both the Canajoharie and Utica are arranged in the sediments so as to reflect the influence of prevailing northeasterly currents.

The increase in abundance of graptolites in the Canajoharie is accompanied by reduction of the bottom-dwelling brachiopods and trilobites profuse in equivalent sediments farther west.

The faunal change presumably is due primarily to the lessened oxygen and increased organic fouling of the bottom waters.

Thinning of the Black River and Trenton deposits near Little Falls gives evidence of a southwest-trending axis of recurrent upwarping termed the Adirondack axis by Kay. The structural conditions of Black River and Trenton times contrast with those of the Late Cambrian and Early Ordovician, since a westward extension of the Adirondack dome is reflected by the absence of sediments of these ages along the western margin of the Adirondacks.

The eastward increase in clay and silt observed in the Trenton sediments of the Mohawk Valley continues in the Hudson Valley. The sediments give evidence of an easterly land area, rising during Trenton time so that first clays and later silty clays and sands were carried farther and farther west.

BLACK RIVER AND TRENTON OF HUDSON VALLEY

Where the Mohawk Valley joins the Hudson Valley near Albany, New York, the upper part of the type Canajoharie shale is replaced by 1,500–2,000 feet of grayish Schenectady shale, containing interlayers of siltstone and fine-grained sandstone (Fig. 23). In varying beds there are graptolitic, brachiopod-trilobite, and cephalopod faunas. Some strata contain numerous eurypterids and may reflect nearer-shore or estuarine-lagoonal, brackish rather than truly marine waters.

The earlier Canajoharie shales found beneath the western part of the Schenectady shale, are replaced in the Albany area 1,000–2,000 feet of grayish, silty and somewhat sandy Snake Hill shales. The Snake Hill shales may have been shifted by the Taconic faults of the Albany region, and it is not certain that they belong beneath the outcropping Schenectady beds in normal stratigraphic succession as

is illustrated in Figure 23. Parts of the Snake Hill shale are graptolitic. Oxygenated, marine bottom waters are represented by other strata that are rich in brachiopods, snails, and trilobites.

The thin Rysedorf conglomerate at the top of the Normanskill shale east and southeast of Albany is definitely one of the deposits of the Taconic plate. It ranges in thickness from one or two feet to 50 feet at a few places. Contained pebbles are fossiliferous, and Ruedemann has discovered in differing pebbles six different faunas ranging in age from Lower Cambrian to Trenton. The faunas are mostly exotic, with groups of species somewhat different from those found in formations of approximately corresponding ages in New York. The pebbles seemingly represent detritus worn from an eastern upfold of strata, which in part were deposited in a trough distinct from New York early Paleozoic basins of sedimentation.

In the Hudson Valley south of the Taconic plate, sediments of Trenton age are represented by the upper part of the Wappinger terrane plus parts of the overlying Ordovician shales. The grayish, silty, and sandy Trenton-age shales both here and near Albany reflect erosion of a more eastern, extensive land surface.

BLACK RIVER AND TRENTON OF NITTANY VALLEY AND MORRISON COVE IN CENTRAL PENNSYLVANIA

The Black River and Trenton sediments of Nittany Valley and Morrison Cove were treated as mappable lithologic units by Charles Butts in his various reports for the Nittany Valley-Morrison Cove region of central Pennsylvania. Thus the top of the Trenton was drawn at the junction of the limestone sequence with the overlying 1,000–1,100 feet of Reedsville shale (Fig. 24). The Trenton limestone was made to include a series of dark, aphanitic, conchoidally fracturing, impure limestones, containing in the upper parts interbeds of finely crystalline gray coquinites and some calcareous shales. The Trenton trilobite, *Cryptolithus tesselatus*, ranges virtually throughout the sequence. *Brongniartella* (*Homalonotus*) *trentonensis* occurs persistently in the lower fourth of the mass. Species of *Rafinesquina*, *Sericeus*, *Dalmanella*, *Calymene*, *Isotelus*, and *Ceraurus* are common to abundant in the higher coquinites.

The dark, aphanitic, sparingly fossiliferous beds of the lower part of the Trenton as mapped by Butts differ markedly in lithology from the underlying, generally bluish gray limestones that he referred to the Black River and Chazyan groups.

The Black River and Trenton sediments of central Pennsylvania have been reinvestigated by Kay (1944), with important additions to knowledge of the stratigraphic relations and diastrophic history of the sediments.

Lower, dark shales of the Reedsville formation, containing *Triarthus eatoni*, have been named Antes Gap shale by Kay and are referred by him to the Trenton group (Fig. 24).

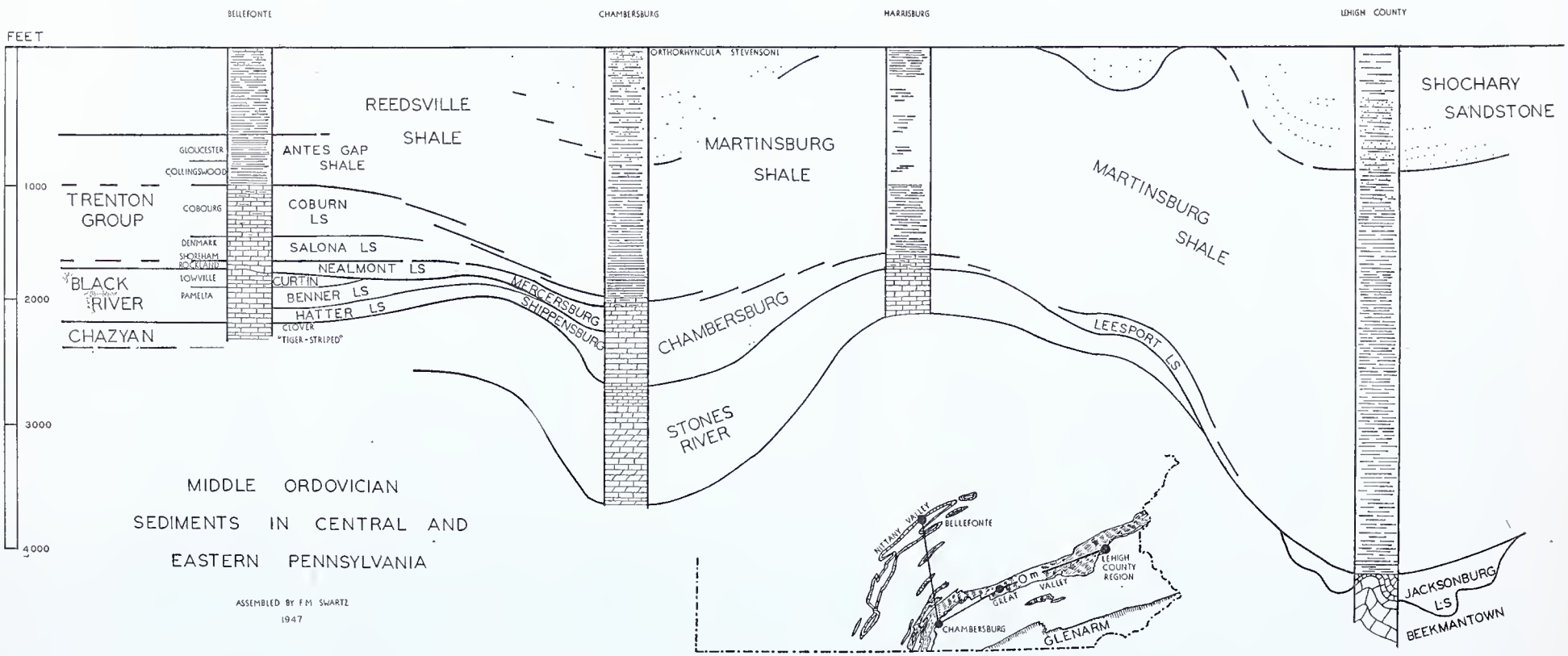


FIG. 24.—Stratigraphy of Middle Ordovician Black River and Trenton sediments from central Pennsylvania to south-central and eastern Pennsylvania.

The Nealmont limestone, included at the base of the Trenton by Kay, is finely crystalline, somewhat argillaceous, and weathers bluish gray. It lacks *Cryptolithus tesselatus* of the overlying limestones, and is characterized especially by *Maclurites* cf. *logani*, whose close relatives are distinctive of the older Chazyan and Beekmantown deposits.

The base of the Nealmont is a disconformity having significant regional effects. However, where the high-calcium Valentine limestone of the next older Curtin beds is missing, the base of the Nealmont is commonly obscure. In general, the lithologic and faunal change at the top of the Nealmont tends to be better marked than that at its base.

The Black River limestones as understood by Kay in Nittany Valley are 400–500 feet thick. They consist for the most part of limestones that weather bluish gray. Some beds are moderately argillaceous and some contain small amounts of silt. The silty residues left after solution are not entirely clastic, but in some layers include minute, doubly terminated quartz crystals and some authigenic feldspars.

The upper or Valentine member of the Curtin division of the Black River group ranges from 40 to 90 feet thick in the Bellefonte region in Nittany Valley, and is one of the purest, high-calcium limestones of the Appalachian region. It is used for chemical lime and is worked near Bellefonte in several deep mines. High-grade limestones occur in some other divisions of the Black River in Nittany Valley and Morrison Cove, but are not so pure as the Valentine quarry ledge.

The Valentine limestone is sparingly fossiliferous, but does contain some *Eoleperditia* and some conodonts. Some other parts of the Black River beds contain brachiopods and trilobites, as well as the coral, *Tetradium*, and some other types of marine fossils.

Several 3- to 6-inch layers of metabentonite occur in the Black River and lower Trenton of central Pennsylvania. They have been used for correlation of sections within the Nittany Valley-Morrison Cove area, and also have been traced to the Great Valley region in southern Pennsylvania and Virginia.

BLACK RIVER AND TRENTON OF GREAT VALLEY NEAR CHAMBERSBURG

In the Great Valley region near Chambersburg, Pennsylvania, and Hagerstown, Maryland, the purer limestones of the Chazyan Stones River formation are overlain by 200–700 feet of more argillaceous limestone named Chambersburg limestone by Stose. Above these in turn are the 2,000 feet or more of Martinsburg shale, sandy in its upper part (Fig. 24).

Trenton faunas occur in the basal part of the Martinsburg, and it was early recognized that parts of the Trenton limestone of central Pennsylvania are represented in the Chambersburg region by the clayey sediments of the lower Martinsburg. It is this change in relation of the basal beds that has led to the usage of Martinsburg for the Ordovician shales near Chambersburg, and Reedsville for their thinner tongue in the Nittany Valley region.

Six members were recognized in the Chambersburg in the Hagerstown-Chambersburg region by Stose (1910) and Bassler (1919), including zones characterized by the coral, *Tetradium cellulosum*, the ball-cystid, *Echinosphaerites*, and the questionable alga or sponge, *Nidulites*. Some of the members seem to wedge in and out by disconformity. Some of the changes in the upper part of the Chambersburg, however, may be related to intertonguing of limestones with shaly beds of Martinsburg type.

The bulk of the Chambersburg limestone was correlated by Stose (1910) and Bassler (1919) with the Black River limestone of New York, largely on the basis of faunal identifications by Ulrich. The basal zone of the Chambersburg was considered possibly to be latest Chazyan, and the topmost zone was thought to be Black River or earliest Trenton.

Recent work by Kay and his associates suggests division of the Chambersburg into Shippensburg limestone, below, and Mercersburg, above. The Shippensburg is thought to be equivalent to the earliest Black River of central Pennsylvania (Fig. 24). Higher parts of the Black River are absent by a disconformity at the boundary of the Shippensburg and Mercersburg strata. The Mercersburg is classed as early Trenton, equivalent to the Nealmont of central Pennsylvania.

The Martinsburg of the Chambersburg region includes 1,000 feet of lower gray and some black shale, calcareous in the basal 100 feet, and 1,000–1,500 feet of upper greenish shale and much interbedded sandstone. The lower 1,000 feet were provisionally classed by Bassler as "Trenton and (?) Utica;" higher parts were correlated with the Eden and Maysville. Fossils were found in only the lower 100 feet of the "Trenton-Utica" division, and the Trenton-Utica age of the remainder of this division is not yet well established.

BLACK RIVER AND TRENTON IN GREAT VALLEY EAST OF CHAMBERSBURG

The Martinsburg shale crops out continuously along the northern part of the Great Valley from Maryland across southeastern Pennsylvania into New Jersey (Fig. 24). Near Harrisburg, the upper sandy beds of the Chambersburg region disappear by unconformity, plausibly because of upwarping and erosion rather than non-deposition. At the base of the Martinsburg, the Chambersburg limestone of the Chambersburg region thins northeastward. It is 100–150 feet thick at Harrisburg, but is not known east of Harrisburg. It is absent at the base of the Martinsburg along the Steelton syncline several miles south of Harrisburg, at least as recognized Chambersburg limestone.

Part of the northeastern disappearance of the Chambersburg is probably due to a facies change into Martinsburg shale.

East of Harrisburg, and also along part of the Steelton syncline south of Harrisburg, shaly limestones occurring at the base of the Martinsburg have been named Leesport limestone by Stose and Jonas from a town 50 miles northeast of Harrisburg. The Leesport limestone at its type locality is 100 feet thick, is shaly, and in its middle part contains some calcareous quartzose sandstone and some

arenaceous limestone. The Leesport beds are extensively quarried for "cement rock."

Fragmentary fossils have been found in the Leesport, but do not furnish close correlations. The Leesport may be a more shaly equivalent of part of the Chambersburg limestone.

Another early Trenton limestone occurs in Lehigh County, eastern Pennsylvania, and is there known as Jacksonburg limestone. A fairly large fauna has been discovered in the limestone and gives evidence of early Trenton, Hull-Rockland age. The Jacksonburg limestone was warped or gently folded, and was locally removed by erosion before deposition of the Martinsburg clays (Fig. 24).

Throughout the Harrisburg-Lehigh County regions of the Great Valley, as near Chambersburg, the thickness of Trenton equivalents included in the Martinsburg remains uncertain.

Local amygdaloidal basalt flows occur at the base of the Martinsburg shale near Jonestown, 25 miles northeast of Harrisburg. The flows rest on Beekmantown limestone. Stose and Jonas have suggested that hard purple and green shales at the base of the Martinsburg in the Jonestown region may represent layers of fine-textured volcanic ash.

At the close of Martinsburg time, the Martinsburg and older strata were folded in eastern Pennsylvania, and the anticlinal arches were considerably eroded before deposition of the overlying sediments.

POSSIBLE BLACK RIVER AND TRENTON RELATIONS SOUTH OF GREAT VALLEY

Black River and Trenton sediments have not definitely been recognized in southeastern Pennsylvania south of the Great Valley.

The Cocalico shale 30 miles southeast of Harrisburg has furnished a few poor graptolites originally identified tentatively with Normanskill or Chazyan species. Purple and greenish shales near the base of the Cocalico are, however, similar to those near the base of the Martinsburg near Jonestown, and suggest that the Cocalico may be early Martinsburg or Trenton in age.

If the Glenarm rocks of southeastern Pennsylvania consist of metamorphosed Paleozoic sediments, sandy clays of Trenton age may be represented in the Wissahickon and Peters Creek schists.

REGIONAL RELATIONS, SEDIMENTATION, AND PALEOGEOGRAPHY OF BLACK RIVER AND TRENTON DEPOSITS IN NEW YORK, PENNSYLVANIA, AND MARYLAND

During Black River time, the New York, Pennsylvania, Maryland region was a nearly flat platform, which was however depressed below sea-level and flooded by shallow seas along a belt extending from the Watertown-Trenton Falls region of north-central New York to the Nittany Valley and Chambersburg areas of central and south-central Pennsylvania. It is probable that the same seas covered

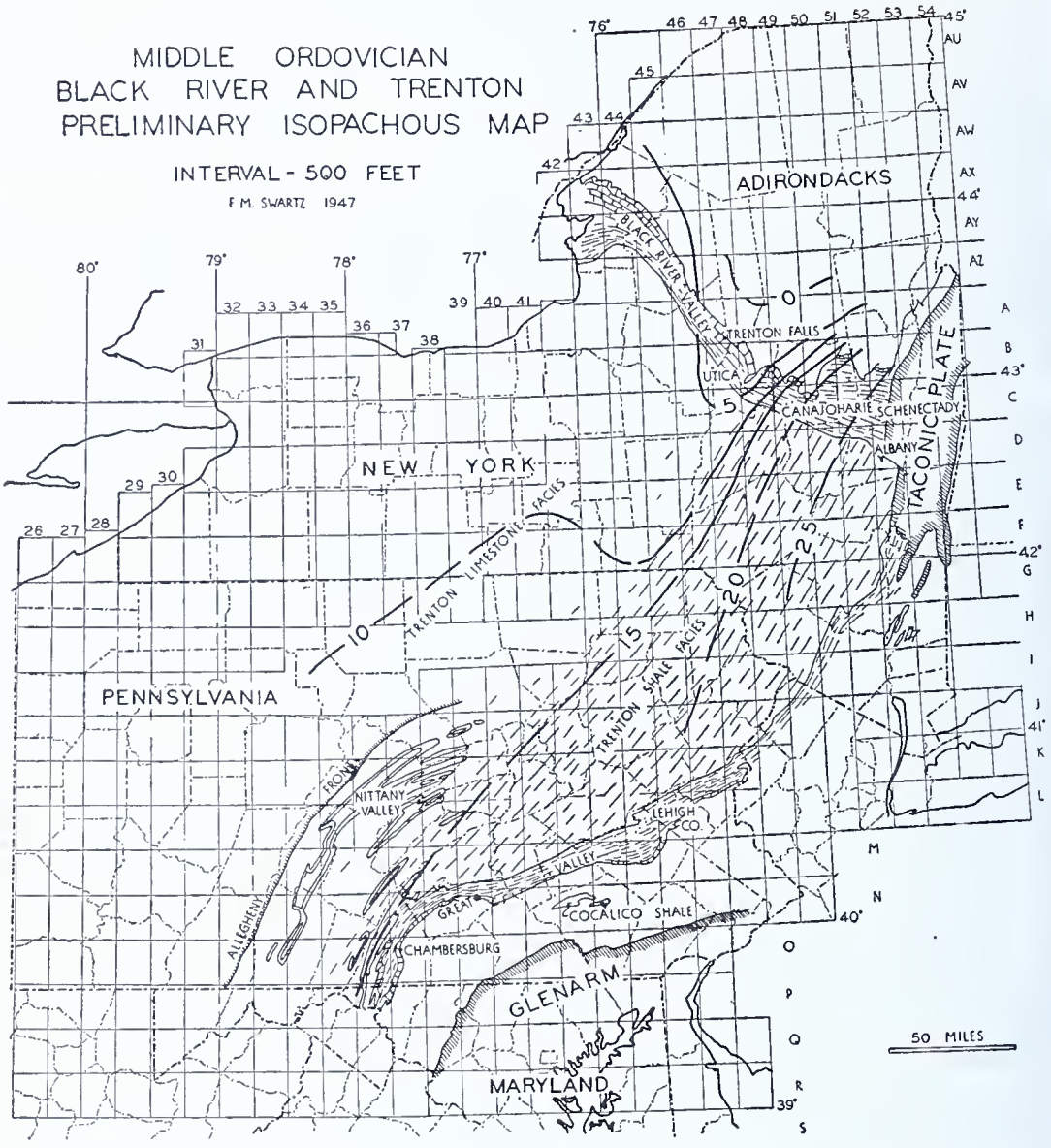


FIG. 25.—Preliminary isopachous map for Middle Ordovician, Black River and Trenton sediments in New York, Pennsylvania, and Maryland. Thickness values used in eastern Pennsylvania are problematical because of uncertainties about proportion of Martinsburg shale that is Trenton in age. True eastern thicknesses may be less than those used in diagram.

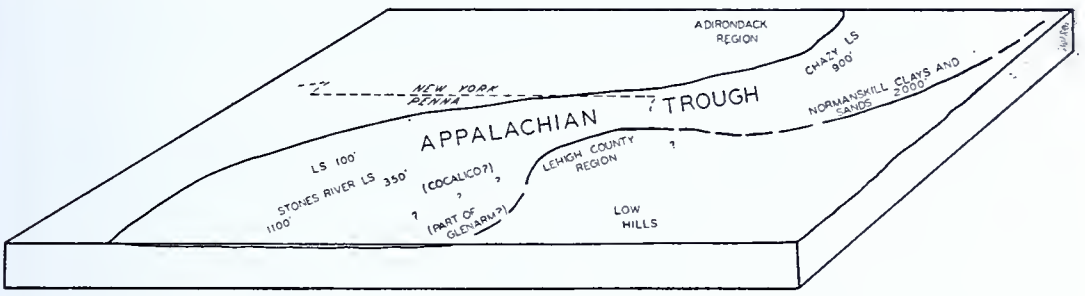
the more western parts of both New York and Pennsylvania during parts of Black River time (Fig. 25).

During Black River time the platform of deposition fluctuated in altitude and underwent gentle, differential warping so that the seas shifted in outline and at times withdrew from large sections of the general region. The central part of the Adirondack region may have stood out of water as a low-surfaced island, and an arch seems to have extended southwestward along Kay's Adirondack

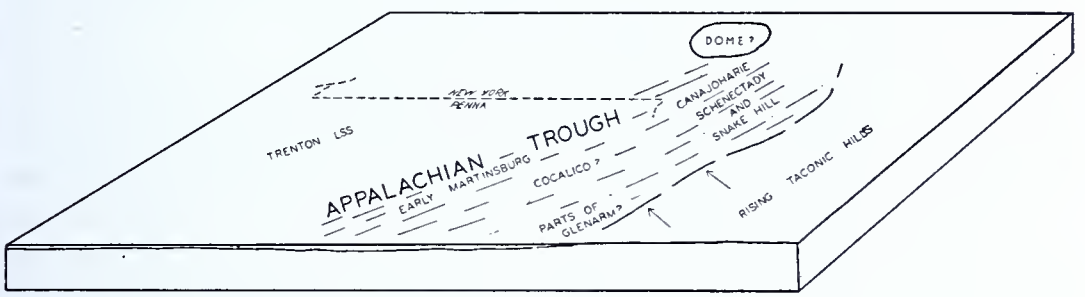
axis. Minor floorings occurred east of this axis along the southeastern and eastern flanks of the Adirondacks.

In southeastern Pennsylvania, deposits of Black River age are not definitely known east of Harrisburg.

Some of the limestones of Black River time are exceptionally pure, and accumulated in basins receiving almost no detritus from surfaces of erosion. Other limestones contain subordinate amounts of clay and a little silt. In some places doubly terminated quartz crystals were formed, perhaps as overgrowths on tiny silt fragments, and some small needles of feldspar crystallized from solution.



PLAUSIBLE PALEOGEOGRAPHY OF CHAZYAN SEDIMENTATION. IT IS NOT CERTAIN WHETHER ANY CHAZYAN SEDIMENTS ARE REPRESENTED IN THE COCALICO AND GLENARM CLASTICS. THE LEHIGH COUNTY REGION MAY HAVE BEEN AN ISLAND RATHER THAN A PROMONTORY.



PLAUSIBLE PALEOGEOGRAPHY OF MIDDLE TRENTON SEDIMENTATION. CLASTICS ERODED FROM THE RISING TACONIC HILLS PASS WESTWARD INTO SHALLOW WATER MARINE LIMESTONES.

FIG. 26.—Plausible paleogeography of Middle Ordovician Chazyan and of Middle Ordovician Trenton sedimentation in New York, Pennsylvania, and Maryland.

Significant clay and sand sediments of Black River age have not been recognized in New York, Pennsylvania, and Maryland. The land sources of the minor clay and silt components of the less pure limestones are not established. In part, such material may have been derived from temporarily emergent parts of the general platform of deposition. In part, they may have been brought in by wind transport rather than by streams.

Chert nodules are not conspicuous in the Black River sediments, except locally as in the late Black River Leray limestone of north-central New York.

A few thin falls of volcanic ash, changed chemically by action of the sea waters in which they fell, are known in Black River sediments in central Pennsylvania,

and one occurs in the Black River near Watertown, New York. Location of the vents from which these ashes were exploded is not well established, but may have been east of the more southern part of the Appalachian trough.

The Black River waters of New York and Pennsylvania were in general marine, and at times supported considerable numbers of corals, brachiopods, and nautiloid cephalopods. Bottom-dwellers, however, were rare in the seas that deposited the highest calcium carbonate sediments, such as the Valentine limestones of central Pennsylvania. Conodonts lived in the Valentine waters, and some *Eoleperditias* were present. Whether presence of these creatures and rarity of the bottom-dwelling brachiopods and trilobites resulted from some special degree of salinity of the waters, from depth, or from some other physico-chemical relationship, is not now clear.

Conditions like those of the Black River age continued into earliest Trenton time, though here limestone-depositing marine waters were more widespread in eastern New York, and also extended into the Jacksonburg limestone area of eastern Pennsylvania. By the beginning of Sherman Fall time, however, lands east of the New York Pennsylvania trough region were affected by the initial stages of the Taconic deformation. As they rose they underwent erosion of increasing vigor and so supplied a flood of clay that spread farther and farther westward onto the platform of sedimentation. Silts and some sands reached areas of Martinsburg sedimentation in Pennsylvania and Snake Hill and Schenectady deposition in eastern New York (Figs. 22, 26).

The western limestones, deposited where bottom waters were well oxygenated, contain numerous brachiopods, bryozoans, and trilobites. Fine clays that accumulated in waters of fair depth, where bottom waters were poorly oxygenated in relation to the fouling action of decomposing organic detritus, generally have few fossils of bottom-dwelling shell life. Some of these contained numerous graptolites excellent for age zonation because of rapidity of their evolution. Farther east, some of the silty clays again represent floors with satisfactorily oxygenated marine waters where brachiopods, trilobites, and mollusks were abundant. Others of these eastern waters may have been inhospitable for the normal life of shallow seas because they were freshened by streams from the eastern land area.

Relations of Trenton and Sub-Trenton at Outcrop in New York, Pennsylvania, and Maryland, with Respect to Oil and Gas Possibilities in Adjoining Subsurface Regions

General considerations

Preliminary suppositions about probable characters of the Trenton-sub-Trenton sediments in their areas of subsurface occurrences in western New York and northern and western Pennsylvania, can be elaborated from the paleogeographic relations and facies trends recognized in the outcrop regions. Implications of the outcrop studies with respect to probable petroleum source beds and reservoir horizons, and thus to oil and gas possibilities of subsurface Trenton and

sub-Trenton sediments of adjoining areas, are considered under the following headings.

General problem of source sediments and reservoir beds
Basement conditions in relation to exploration
Oil and gas possibilities of Lower Cambrian
Oil and gas possibilities of Middle and Upper Cambrian
Oil and gas possibilities of Lower Ordovician
Oil and gas possibilities of Middle Ordovician

It must be recognized that at this stage of information, comments can be offered on only a very tentative and provisional basis.

GENERAL PROBLEM OF SOURCE SEDIMENTS AND RESERVOIR HORIZONS

Regional stratigraphic studies, such as those here summarized for the Trenton and sub-Trenton of New York, Pennsylvania, and Maryland, may contribute significant conclusions about petroleum possibilities since they give information about facies trends of probable source beds, about horizons of potential original porosities, and about depositional and post-depositional tectonic events significant in effects on reservoirs and on petroleum migrations.

Opinions are in conflict about many questions concerning source sediments of petroleum. There is, however, general agreement that special promise is given by near-source, shallow-water suites of clastic marine and estuarine-lagoonal deposits formed under conditions of relatively rapid accumulation. Petroleum occurrences in thick limestone-dolomite sequences indicate that shallow-water marine carbonates may likewise be significant as source horizons.

Potential reservoir horizons giving promise of porosity because of features of original deposition, primarily include well washed near-shore marine and estuarine-lagoonal sheet sands and beach sands. These sediments will tend to possess significant original porosity and permeability, and also are likely to have had favorable association with source sediments rich in organic remains.

Interstitial openings in clastic limestones and coquinas may serve as first-stage reservoirs, but will probably undergo compaction and self-cementation as burial proceeds during subsequent sedimentation.

The tectonic history of the basin during deposition is significant not only because of effects on paleogeography and thus on the characters and geographic distribution of the varying sedimentary facies; but also because local, temporary emergence of parts of the surface of deposition may produce potential reservoir porosities by weathering and leaching of upwarped areas of limestones and dolomites, or of calcareous or dolomitic sands.

The timing of entry of oil and gas into reservoir beds affects the nature, distribution, and maintenance of reservoir porosities.

From Cenozoic petroleum, it is evident that Trenton-sub-Trenton oil and gas must in large part have entered early-stage reservoirs long before the Appalachian folding of Late Paleozoic time. Regional westward and northwestward, updip rise of the early Paleozoics, associated with the pronounced westward con-

vergence of the overlying Paleozoic sediments, must have significantly affected Paleozoic migrations. Migration related to such regional rise was of course modified by any early structural arches associated with the depositional history of the region, as well as by patterns of permeability associated with deposition, with cementation, and with leaching during emergences.

Once emplaced in a reservoir, the oil and gas accumulations presumably helped to maintain porosities by reducing if not preventing further cementation by ground water. Cementation in adjacent extensions of the same bed, may in some cases have locked the oil and gas in place during subsequent tiltings.

In Pennsylvania and New York, the post-depositional tectonic history of the Appalachian trough region is significant because the changing dips would tend to cause migration from early-stage to late-stage reservoirs. Tectonic effects as well as deep burial probably affected porosities by both compaction and cementation. Tectonic pressures and temperatures have evidently modified the petroleum substances themselves, as well as the containing sediments. However, in view of the known exceptions, the carbon-ratio theory as originally postulated by David White should not be fully accepted as a guide limiting eastward exploration in the Appalachian region.

BASEMENT CONDITIONS IN RELATION TO EXPLORATION

The basement conditions of the Pennsylvania-New York region are of interest in connection with future oil and gas exploration of deep formations partly because of their influence on and relation to geologic structures of the overlying sediments, and partly because of their effects on geophysical prospecting.

So far as is known, the surface of the pre-Cambrian in Pennsylvania, New York, and Maryland did not have erosional relief sufficient in amplitude to produce significant structural features in the overlying Paleozoic sediments. Actual knowledge of the contact relations is, however, restricted to eastern parts of the three states.

In eastern Pennsylvania, it is clear that the surficial parts of the pre-Cambrian were deformed during the Appalachian folding in reasonable accord with the larger folds in the Paleozoic sediments.

If the folding of the Paleozoic sediments during Appalachian deformation was largely a response to plastic shortening of the basement in the fashion discussed in an earlier chapter, it is probable that the surface of the pre-Cambrian generally is arched under the major anticlines, depressed under corresponding synclines.

There is some evidence that various Appalachian folds were incipiently active during Paleozoic sedimentation. If this assumption is correct, the incipient activity may well have resulted from stresses active in the basement. Whatever the ultimate cause, any fold activity accompanying sedimentation would be significant in relation to reservoir possibilities.

In their areas of exposure, the pre-Cambrian rocks of New York, Pennsylvania, and Maryland are geologically complex. Throughout the region of the

three states, similar geologic complexity can be expected. The geologic complexities will probably be reflected in both magnetic and gravimetric types of geophysical surveys.

The largest gravimetric anomaly of the New York, Pennsylvania region is a great low paralleling the eastern part of the belt of the folded Appalachians along or northwest of the Hagerstown-Harrisburg-Allentown Valley and its continuations. This major low may be associated with plastic thickening, during the Appalachian deformation, of a basement mass lighter than subjacent rock materials.

Next-order gravimetric and probably magnetic anomalies will probably be associated with large-scale geologic complexities of pre-Cambrian rocks of the surficial parts of the basement. In some areas, especially near Philadelphia and Baltimore, there are igneous bodies of probable Late Paleozoic age that may be large enough to cause significant anomalies, and along the Triassic belt crossing the southeastern part of Pennsylvania there are extensive Triassic diabases. Some small basic intrusives of uncertain age occur in western Pennsylvania.

Geophysical anomalies reflecting the small-amplitude folds west of the Appalachian front will probably be small in value and difficult to distinguish with reasonable confidence.

OIL AND GAS POSSIBILITIES OF LOWER CAMBRIAN

Oil and gas possibilities of the Lower Cambrian sediments of the Pennsylvania-New York region are affected by (1) geographic distribution of the sediments; (2) changes in regional metamorphism; (3) facies in relation to source and reservoir conditions; (4) general structural conditions and depths of burial.

So far as can be judged from present information, Lower Cambrian sediments are probably restricted in New York to the vicinity of the Hudson River Valley; in Pennsylvania they reach their greatest known thickness in the south-central part of the state; they plausibly thin toward the west, northwest, and north in their regions of subsurface extent, and it is improbable that they reach the northern and western borders of Pennsylvania.

In their outcrop regions in south-central and southeastern Pennsylvania, the Lower Cambrian sediments show the effects of low-grade but well defined regional metamorphism. Structural relations of planes of schistosity indicate that much if not all of the metamorphism accompanied the Late Paleozoic Appalachian folding. The Appalachian metamorphism can be expected to decrease in intensity toward the west and north, with consequent waning of its tendency to dissipate Paleozoic accumulations of oil and gas.

The Lower Cambrian sediments of the South Mountains region of south-central Pennsylvania, and of outcrop belts farther east, include thick sand deposits that at the time of deposition should have had favorable reservoir-type porosities. Direction of sedimentary transport at the time of accumulation of these sands is not wholly clear, but derivation seems to have been from the south-

east. If this view is correct, the sand formations should thin and become finer-grained toward the west and northwest. It is not impossible that near the northwesterly margin of the Lower Cambrian trough there may be sand bodies derived from land surfaces on the north and northwest.

Carbonates and some sandy sediments of the upper fourth of the Lower Cambrian in south-central Pennsylvania contain marine fossil faunas. The well washed character and wide extent of some of the underlying sands suggest deposition in shallow marginal regions of the Lower Cambrian seas. Some other parts of the Lower Cambrian sands, silts, and gravels may be alluvial. Marine-estuarine sediments of promise as source and reservoir beds probably continue in the western and northern, subsurface extensions of the Lower Cambrian sediments, but evidence is meager.

Structurally, the Cambro-Ordovician strata exposed in Nittany Valley and Morrison Cove in central Pennsylvania, plunge westward and northwestward deep beneath the younger strata of the Allegheny Front and Allegheny Plateau region. Along the Front, the expected depth of the Lower Cambrian sediments is about 20,000 feet. Toward the west, northwest, and north in Pennsylvania, the depth of the thinning, marginal parts of the Lower Cambrian is expected to lessen in accordance with the well marked convergence of the overlying Paleozoic strata. At Bradford, Pennsylvania, the depth of the horizon of the Lower Cambrian is probably 10,000–12,000 feet, though it is less clear that Lower Cambrian sediments can be expected to extend to this geographic area.

The expected updip pinch-out of the Lower Cambrian in western and northern Pennsylvania could provide significant stratigraphic traps, if porosities have not been too greatly reduced, and if the oil and gas have not been dispersed or destroyed by the combination of deep burial and the heat and stresses of the Appalachian mountain-making.

In summary, Lower Cambrian sediments and hence any possibilities of Lower Cambrian oil and gas probably are restricted in New York to a belt adjacent to the Hudson River Valley. In Pennsylvania, Lower Cambrian sediments should lie at depths of 20,000 feet for some distance west of the Allegheny Front, well below levels of probable exploration for a considerable time to come. With convergence of overlying strata, the Lower Cambrian sediments rise to lesser depths toward the north, northwest, and west, and probably thin and disappear before reaching the northern and western boundaries of Pennsylvania. This updip wedge-out of the Lower Cambrian may provide structural conditions favorable for stratigraphic traps; but the expected depths would make exploration costly.

In the folded Appalachian area of central Pennsylvania, there are various anticlinal axes where the Lower Cambrian can be expected to occur in considerable thicknesses and at depths that are not excessive for drilling. Metamorphism should be less than in the outcrop areas of the South Mountains and more eastern parts of Pennsylvania, but the effects of Appalachian deformation

may still be significant in limiting the oil and gas possibilities of the strata. Reservoir possibilities, if present, must be sought in fracture complexes or in sandstone pockets protected from cementation by contained oil and gas.

OIL AND GAS POSSIBILITIES OF MIDDLE AND UPPER CAMBRIAN

In contrast to the other Trenton-sub-Trenton strata of the Pennsylvania-New York region, the Middle and Upper Cambrian sediments include extensive bodies of quartzose sands believed to have been derived from the north and northwest. These sands therefore probably thicken in the region of their subsurface extension northwest and north of the Appalachian Front of central Pennsylvania, affording possibilities of significant reservoirs.

The sandy sediments of the Middle and Upper Cambrian strata of central Pennsylvania occur chiefly in the Gatesburg formation, with two thin, local sandstone bodies in the subjacent Warrior limestone. The Gatesburg sandstones are interbedded with dolomites; they consist of cleanly washed quartz sand with some feldspar, and in large part are probably dolomitic where unweathered. The sandstones and the predominating dolomites were deposited in shallow waters fluctuating in depth, and in their northwestern subsurface extensions may include bodies that suffered temporary emergence with improvement of porosities by leaching.

Like the Lower Cambrian strata beneath them, the Middle and Upper Cambrian formations plunge from surface or near-surface levels along Nittany Valley and Morrison Cove in central Pennsylvania, to depths of 15,000 and possibly 20,000 feet in the near-by region of the Allegheny Front. They should remain at great depths for some distance west and northwest of the Front, and in this belt assumably are arched by the northern parts of the Laurel Hill and Chestnut Ridge anticlines. Farther west and northwest they are expected to rise in accordance with convergence of the overlying younger strata, the gentle updip gradient modified by various anticlinal and synclinal folds that decrease in amplitude northwestward across the strike.

The northwestward convergence of the post-Cambrian Paleozoic sediments of western Pennsylvania is well marked, and is sufficient to suggest that the Upper Cambrian deposits had a distinct northwestward regional rise well before the time of Appalachian folding. Insofar as this regional rise was not significantly interrupted by early-stage arches, and to the extent that permeability of the reservoir beds were continuous across the area, extensive updip migrations of oil and gas probably occurred, with loss of these substances from the deeper areas. If on the other hand, there were significant early-stage arches, or if permeability patterns of deposition, leaching, or cementation caused retention of the oil and gas in localized regions, then migration up the regional rise would be less significant. In any event, distribution of any oil or gas remaining to-day in the Middle and Upper Cambrian of western Pennsylvania must have been greatly affected by the history of these sediments prior to the time of Appalachian folding.

Although the Middle and Upper Cambrian strata rise west of the Allegheny Front in Pennsylvania in accord with the convergence of younger strata, they remain at depths where exploration will be costly. Near Bradford their upper surface is probably about 10,000 feet below ground level. They rise to shallower levels northward across the western part of New York.

The interbedded dolomites and sandstones of the Gatesburg formation of central Pennsylvania find their facies counterparts in the Theresa deposits of the southern and northern margins of the Adirondacks, and are the approximate age equivalents of the Theresa and associated Potsdam formations. Sandy dolomitic rocks of Potsdam-Theresa age probably underlie much of the region south of the Adirondacks and west of the Hudson River Valley in New York. They are expected to wedge out updip above the surface of the pre-Cambrian in the general vicinity of the southwestern margin of the Adirondacks, where all of the Cambrian strata are absent by unconformity.

Sandy phases of the Middle and Upper Cambrian have fair promise for oil or at least gas in western New York and north-central, northwestern, and western Pennsylvania. In regions where folds are strong enough to give promise of some structural control of reservoirs, the Middle and Upper Cambrian sediments generally occur at depths of 10,000 feet and more. In shallower depths of occurrence, there will generally be lack of structural control and necessity of search for stratigraphic traps alone.

In central Pennsylvania, the Gatesburg dolomite-sandstone formation is breached by erosion in the anticlines of Nittany Valley and Morrison and Friends Coves. It lies below ground and may deserve testing along the axes of some other anticlines in the region.

OIL AND GAS POSSIBILITIES OF LOWER ORDOVICIAN

The Lower Ordovician sediments of the Nittany Valley region of central Pennsylvania comprise a 3,000- to 4,000-foot succession, composed three-fourths of dolomites and one-fourth of limestones. There is one locally developed body of quartzitic sandstone, ranging to nearly 20 feet in thickness.

The border lands of the Appalachian platform of deposition, including the emergent area of the Adirondack region, seem to have been low in altitude during Beekmantown time. Accordingly, it does not seem probable that large bodies of sandstone will be found in the Beekmantown sediments in their regions of subsurface extent through western New York and northern and western Pennsylvania. There may of course be minor tongues and lenses of sand washed from the north in a manner reminiscent of Upper Cambrian paleogeography.

The thin sandstone of the upper part of the Beekmantown near Bellefonte, and some thin sandstones in the Beekmantown near Chambersburg, reflect activity of the platform of deposition during Beekmantown time. There has been some suggestion that the thin sandstone near Bellefonte may be a tongue from the widespread Chazyan St. Peter sandstone of the northern Mississippi Valley

region. The age correlation and source-direction of the sandstone near Bellefonte are not yet closely enough established to furnish a final answer to this problem. Krynine has, however, published petrologic evidence that elements of the sandstone near Bellefonte were derived from upwarped Upper Cambrian Gatesburg sandy dolomite, or its petrographically similar continuations.

In the subsurface areas north and northwest of the Nittany Valley region of central Pennsylvania, the Beekmantown sediments probably thin like those shown in Figure 20. The thinned parts may represent less continuous deposition and, if so, were probably affected by local emergence and weathering during parts of Beekmantown time. If such emergence and weathering did occur, favorable reservoir-type porosites may have been developed locally by solution and leaching of the Beekmantown strata. Where the Beekmantown is thin, and uparching favorable, breaching of the Beekmantown may have uncovered limited areas of the sandy Gatesburg.

Oil and gas possibilities of porous zones developed by local emergence and leaching of the Beekmantown would be greatly enhanced if the lines of emergence followed axes inherited by anticlines of the Appalachian folding.

The proportion of dolomite versus limestone in the Beekmantown succession is greater in central than in southeastern Pennsylvania. This regional change favors the view that the Beekmantown deposits are probably predominantly dolomites rather than limestones in the subsurface areas of western and northern Pennsylvania and western New York.

It is reasonably clear that the dolomitization of the Beekmantown of central Pennsylvania is in general paradepositional, and not related to surfaces of unconformity. The extensive dolomitization of the Beekmantown strata in Nittany Valley is not connected with known large-scale slump structures antedating the present erosional cycle, and is not plausibly a source of significant shrinkage porosity. Porosity might, however, be developed in dolomites and dolomitic limestones by differential leaching of limestone constituents during emergence and exposure to weathering.

The fine-textured Bellefonte dolomite of the upper Beekmantown of Nittany Valley is cut by more numerous joints than are most adjoining formations. Assumably the joints are related to Appalachian folding and if so would not have furnished early-stage reservoir porosities.

The coarser-textured beds of the Nittany dolomite, below the middle of the Beekmantown in Nittany Valley, have vug-like cavities, some open for several hundred feet below the surface where cut by well cores. Permeability of the walls of the vugs is low.

In summary, it appears that any significant reservoir porosities in the northwestward, subsurface extensions of the Beekmantown are probably to be dependant on uparching, leaching, and erosion related to unconformities. Some sandstones may be present, either as thin tongues brought in from northerly marginal lands or as lenses bordering upwarped and eroded areas of the pre-Beekmantown

Gatesburg strata. Vugs occur in the Nittany dolomite, but may not be numerous enough or well enough connected to provide important reservoir porosities. Some fracture porosity is present in the fine-textured Bellefonte dolomite, but was not available for early-stage migrations.

OIL AND GAS POSSIBILITIES OF MIDDLE ORDOVICIAN

Through their subsurface areas in south-central and southwestern New York and northern and western Pennsylvania, the Middle Ordovician Chazy, Black River, and Trenton sediments mostly are limestones.

Some shales occur at the top of the Trenton even in the western parts of the region, if Kay's usage is employed for the group.

East of a line from Little Falls, New York, along a path east of Nittany Valley but west of Chambersburg in Pennsylvania, the limestones of the middle and late parts of Trenton time pass laterally into clay shales. Still farther east, the shales contain increasing quantities of silt and some sand.

Even in the most easterly Trenton-age sediments of the subsurface areas in New York and Pennsylvania, it is improbable that sandstones occur in bodies sufficient to serve as significant reservoirs. The late Martinsburg sandstones of eastern Pennsylvania probably are post-Trenton in age.

Favorable reservoir conditions in the Chazy, Black River, and Trenton sediments of New York and Pennsylvania are hence dependent on features of the limestone sediments.

Disconformities occur at several horizons in the Chazy, Black River, and Trenton limestones in their outcrop areas in north-central New York and central Pennsylvania.

It is probable that the disconformities observed in the outcrop belts are persistent in the subsurface areas farther west. The emergent stages represented by the disconformities may at places be associated with solution and solution-slump features that could serve as reservoirs. If dolomitization occurred in any of the zones of weathering, local shrinkage porosities may have been formed.

Porosities produced by solution and weathering will be difficult to locate unless they are related to arches which were weakly active during the general period of deposition, and which by structural inheritance are reasonably coincident with present anticlinal axes. Though present evidence is inadequate, especially for the older and deeper strata, the possibility of early crustal activity along present anticlines will merit consideration in any future plans for deep tests.

Some of the natural-gas occurrences in Trenton limestones in central New York seem to be related to the trapping action of shale interlayers. Shale interlayers can be expected in higher parts of the Trenton limestones of subsurface areas in New York and Pennsylvania, even if the limestone-shale boundary is transgressive in age.

Commercial production of natural gas in the Trenton limestone in central

New York gives some promise for occurrences in the Middle Ordovician limestones in southern New York and Pennsylvania. The increased depths in these southern areas will of course greatly increase costs of exploration and production.

BIBLIOGRAPHY

ALLING, H. L., 1919, "Geology of the Lake Clear Region," *New York State Mus. Bull. 207–8*, pp. 11–145.

BAILEY, E. B., 1936, "Sedimentation in Relation to Tectonics," *Bull. Geol. Soc. America*, Vol. 47, pp. 1713–25.

BALK, R., 1930, "Structural Survey of the Adirondack Anorthosite," *Jour. Geol.*, Vol. 38, No. 4, pp. 289–302.

———, 1932, "Geology of the Newcomb Quadrangle," *New York State Mus. Bull. 290.* 106 pp.

BASCOM, FLORENCE, 1896, "The Ancient Volcanic Rocks of South Mountain, Pennsylvania," *U. S. Geol. Survey Bull. 136.* 124 pp.

———, 1905, "Piedmont District of Pennsylvania," *Bull. Geol. Soc. America*, Vol. 16, pp. 289–328.

———, 1909, "Description of the Philadelphia District," *U. S. Geol. Survey Geol. Atlas Folio 162.* 23 pp.

———, AND MILLER, B. L., 1920, "Description of the Elkton and Wilmington Quadrangles," *ibid., Folio 211.* 22 pp.

———, AND STOSE, G. W., 1932, "Description of the Coatesville and West Chester Quadrangles," *ibid., Folio 223.* 15 pp.

———, AND STOSE, G. W., 1938, "Geology and Mineral Resources of the Honeybrook and Phoenixville Quadrangles, Pennsylvania," *U. S. Geol. Survey Bull. 891.* 145 pp.

BASSLER, R. S., 1919, "Cambrian and Ordovician," *Maryland Geol. Survey.* 424 pp.

BAYLEY, W. S., 1941, "Pre-Cambrian Geology and Mineral Resources of the Delaware Water Gap and Easton Quadrangles, Pennsylvania and New Jersey," *U. S. Geol. Survey Bull. 920.* 98 pp.

BERKEY, C. P., AND RICE, MARION, 1921, "Geology of the West Point Quadrangle," *New York State Mus. Bull. 225–26.* 152 pp.

BLISS, E. F., AND JONAS, A. I., 1916, "Relation of the Wissahickon Mica Gneiss to the Shenandoah Limestone and Octoraro Schist of the Doe Run and Avondale Region, Chester County, Pennsylvania," *U. S. Geol. Survey Prof. Paper 98*, pp. 9–34.

BRAINERD, E., 1891, "The Chazy Formation of the Champlain Valley," *Bull. Geol. Soc. America*, Vol. 2, pp. 293–300.

———, AND SEELY, H. M., 1888, "The Original Chazy Rocks," *Amer. Geologist*, Vol. 2, pp. 323–30.

———, AND SEELY, H. M., 1890, "The Calciferous Formation in the Champlain Valley," *Bull. Amer. Mus. Nat. Hist.*, Vol. 3, pp. 1–23.

BROEDEL, CARL H., 1937, "The Structure of the Gneiss Domes near Baltimore, Maryland," *Maryland Geol. Survey*, Vol. 13, pp. 149–87.

BUDDINGTON, A. F., 1934, "Geology and Mineral Resources of the Hammond, Antwerp, and Lowville Quadrangles," *New York State Mus. Bull. 296.* 251 pp., 4 maps.

———, 1937, "Geology of the Santa Clara Quadrangle," *ibid., Bull. 309.* 56 pp.

———, 1939, "Adirondack Igneous Rocks and Their Metamorphism," *Geol. Soc. America Mem. 7.* 354 pp.

BUTTS, CHARLES, 1945, "Description of the Hollidaysburg and Huntingdon Quadrangles," *U. S. Geol. Survey Geol. Atlas Folio 227.* 20 pp., maps.

———, AND MOORE, E. S., 1936, "Geology and Mineral Resources of the Bellefonte Quadrangle, Pennsylvania," *U. S. Geol. Survey Bull. 855.* 111 pp.

———, SWARTZ, F. M., AND WILLARD, BRADFORD, 1939, "Geology and Mineral Resources of the Tyrone Quadrangle," *Pennsylvania Topog. and Geol. Survey Atlas 96*, 4th Ser. 118 pp.

CADY, WALLACE, M. 1945, "Stratigraphy and Structure of West Central Vermont," *Bull. Geol. Soc. America*, Vol. 56, pp. 515–88; 10 pls., 6 figs.

CHADWICK, G. H., 1920, "The Paleozoic Rocks of the Canton Quadrangle," *New York State Mus. Bull. 217–18*, pp. 1–60; 12 pls.

CLARK, T. H., 1921, "A Review of the Evidence for the Taconic Revolution," *Proc. Boston Soc. Nat. Hist.*, Vol. 36, No. 3, pp. 135–63.

———, 1924, "The Paleontology of the Beekmantown Series at Levis, Quebec," *Bull. Amer. Paleon.*, Vol. 10, No. 41. 135 pp.

CLARKE, J. M., AND SCHUCHERT, C., 1899, "The Nomenclature of the New York Series of Geological Formations," *Science*, New Ser., Vol. 10, pp. 874–78; *Amer. Geol.*, Vol. 25 (1900), pp. 114–19.

CLOOS, ERNST, 1937, "The Application of Recent Structural Methods in the Interpretation of the Crystalline Rocks of Maryland," *Maryland Geol. Survey Rept.*, Vol. 13, pp. 27–105.

———, 1940, "Crustal Shortening and Axial Divergence in the Appalachians of Southeastern Pennsylvania and Maryland," *Bull. Geol. Soc. America*, Vol. 51, No. 6, pp. 845–72.
———, 1943, "Method of Measuring Changes of Stratigraphic Thickness Due to Flowage and Folding," *Trans. Amer. Geophys. Union, 24th Ann. Mtg.*, Part I, Reports and Papers, Tectonophysics, pp. 273–80.
———, AND HERSHEY, H. G., 1936, "Structural Age Determination of Piedmont Intrusives in Maryland," *Proc. Nat. Acad. Sci.*, Vol. 22, No. 1, pp. 71–80.
———, AND HIETANEN, A., 1941, "Geology of the 'Martic Overthrust' and the Glenarm Series in Pennsylvania and Maryland," *Geol. Soc. America Spec. Paper 35*. 207 pp.
COHEN, CHARLES J., 1937, "Structure of the Metamorphosed Gabbro Complex at Baltimore, Maryland," *Rept. Maryland Geol. Survey*, Vol. 13, pp. 215–36.
CUSHING, H. P., 1899, "Report on the Boundary Between the Potsdam and Pre-Cambrian Rocks North of the Adirondacks," *New York State Mus. 50th Ann. Rept. for 1896*, Pt. 2, pp. 1–27.
———, 1900, "Preliminary Report on the Geology of Franklin County, New York," *New York State Mus. 52d Ann. Rept. for 1898*, Vol. 2, pp. 73–128, map.
———, 1905, "Geology of the Northern Adirondack Region," *New York State Mus. Bull. 95*, pp. 271–453.
———, 1905a, "Geology of the Vicinity of Little Falls, Herkimer County," *ibid., Bull. 77*. 95 pp.
———, 1908, "Lower Portion of the Paleozoic Section in Northwestern New York," *Bull. Geol. Soc. America*, Vol. 19, pp. 155–76.
———, FAIRCHILD, H. L., RUEDEMANN, R., AND SMYTH, C. H., JR., 1910, "Geology of the Thousand Islands Region," *New York State Mus. Bull. 145*, pp. 1–194.
———, AND RUEDEMANN, R., 1914, "Geology of Saratoga Springs and Vicinity," *ibid., Bull. 169*. 177 pp.
———, AND NEWLAND, D. H., 1925, "Geology of the Gouverneur Quadrangle," *ibid., Bull. 259*. 122 pp., map.
DALE, T. N., 1899, "The Slate Belt of Eastern New York and Western Vermont," *U. S. Geol. Survey 19th Ann. Rept.*, pp. 153–300.
———, 1904, "Geology of the Hudson Valley Between the Hoosic and the Kinderhook," *U. S. Geol. Survey Bull. 242*. 63 pp.
DARTON, N. H., 1892, "Fossils in the 'Archean' Rocks of the Central Piedmont, Virginia," *Amer. Jour. Sci.*, 3d Ser., Vol. 44, pp. 50–52.
DRESSER, J. A., 1925, "The Magog Conglomerate; a Horizon Mark in the 'Quebec Group,'" *Proc. and Trans. Royal Soc. Canada*, Ser. 3, Vol. 19, Sec. 4, pp. 115–21.
FETTKE, C. R., 1914, "The Manhattan Schist of Southeastern New York State and Its Associated Igneous Rocks," *Annals New York Acad. Sci.*, Vol. 23, pp. 245–57.
FRAZER, PERSIFOR, JR., 1884, "The Peach Bottom Slates of Southeastern York and Southern Lancaster Counties, Pennsylvania," *Trans. Amer. Inst. Min. Eng.*, Vol. 12, pp. 355–59.
GORDON, C. E., 1911, "Geology of the Poughkeepsie Quadrangle," *New York State Mus. Bull. 148*. 121 pp.
GRIGGS, DAVID, 1939, "A Theory of Mountain-Building," *Amer. Jour. Sci.*, Vol. 237, No. 9, pp. 611–50.
HARTNAGEL, C. A., 1938, "The Medina and the Trenton of Western New York," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 22, No. 1, pp. 79–99.
HAWKES, H. E., JR., 1941, "Roots of the Taconic Fault in West-Central Vermont," *Bull. Geol. Soc. America*, Vol. 52, No. 5, pp. 649–66.
HAWKINS, A. C., 1924, "Alternative Interpretation of Some Crystalline Schists in Southeastern Pennsylvania," *Amer. Jour. Sci.*, 5th Ser., Vol. 7, pp. 355–64.
HERSHEY, H. GARLAND, 1937, "Structure and Age of the Port Deposit Granodiorite Complex," *Rept. Maryland Geol. Survey*, Vol. 13, pp. 107–48.
HESS, H. H., 1938, "Gravity Anomalies and Island Arc Structure with Particular Reference to the West Indies," *Proc. Amer. Phil. Soc.*, Vol. 79, No. 1, pp. 71–96.
HOLZWASSER, F., 1926, "Geology of Newburgh and Vicinity," *New York State Mus. Bull. 270*. 95 pp.
HONESS, A. P., AND GRAEBER, C. K., 1926, "Petrography of the Mica Peridotite Dike at Dixonville, Pennsylvania," *Pennsylvania State College Min. Met. Exp. Sta. Bull. 2*. 16 pp.
———, AND JEFFRIES, C. D., 1940, "Authigenic Albite from the Lowville Limestone at Bellefonte, Pennsylvania," *Jour. Sed. Petrology*, Vol. 10, pp. 12–18.
INGERSON, EARL, 1939, "Comparison of the Fabrics of Inclusions and the Adjacent Intrusive Rock," *Amer. Mineralogist*, Vol. 24, No. 10, pp. 607–23.
JONAS, A. I., 1924, "Pre-Cambrian Rocks of the Western Piedmont of Maryland," *Bull. Geol. Soc. America*, Vol. 35, No. 2, pp. 355–63.
———, 1929, "Structure of the Metamorphic Belt of the Central Appalachians," *ibid.*, Vol. 40, No. 2, pp. 503–13.

———, AND STOSE, G. W., 1930, "Geology and Mineral Resources of the Lancaster Quadrangle, Pennsylvania," *Pennsylvania Geol. Survey, Topog. and Geol. Atlas 168*, 4th Ser. 106 pp.
———, AND STOSE, G. W., 1926, "Geology and Mineral Resources of the New Holland Quadrangle, Pennsylvania," *ibid., Atlas 178*. 40 pp.
———, 1937, "Tectonic Studies in the Crystalline Schists of Southeastern Pennsylvania and Maryland," *Amer. Jour. Sci.*, 5th Ser., Vol. 34, No. 203, pp. 364–88.
———, AND STOSE, G. W., 1937, "Age Reclassification of the Frederick Valley Limestones," *Bull. Geol. Soc. America*, Vol. 47, No. 10, pp. 1657–74.
———, AND STOSE, G. W., 1938, "Geologic Map of Frederick County and Adjacent Parts of Washington and Carroll Counties," *Maryland Geol. Survey*, map.
———, AND STOSE, G. W., 1938, "New Formation Names Used on the Geologic Map of Frederick County, Maryland," *Jour. Washington Acad. Sci.*, Vol. 28, No. 8, pp. 345–48.
———, AND STOSE, G. W., 1939, "Age Relations of the Pre-Cambrian Rocks in the Catoctin Mountains-Blue Ridge and Mount Rogers Anticlinoria in Virginia," *Amer. Jour. Sci.*, Vol. 237, pp. 575–93.
KAY, G. MARSHALL, 1933, "The Ordovician Trenton Group in Northwestern New York: Stratigraphy of the Lower and Upper Limestone Formations," *ibid.*, 5th Ser., Vol. 26, pp. 1–15.
———, 1937, "Stratigraphy of the Trenton Group," *Bull. Geol. Soc. America*, Vol. 48, pp. 233–302.
———, 1942, "Ottawa-Bonnechere Graben and Lake Ontario Homocline," *ibid.*, Vol. 53, No. 4, pp. 585–646.
———, 1942a, "Development of the Northern Allegheny Synclinorium and Adjoining Regions," *ibid.*, Vol. 53, No. 11, pp. 1601–57.
———, 1943, "Chemical Lime in Central Pennsylvania," *Econ. Geology*, Vol. 38, No. 3, pp. 188–203.
———, 1944, "Middle Ordovician of Central Pennsylvania," *Jour. Geol.*, Vol. 52, pp. 1–23, 97–116.
———, 1945, "Highgate Springs Sequence, Northwestern Vermont and Southeastern Quebec" (abstract), *Bull. Geol. Soc. America*, Vol. 56, No. 12, Pt. 2, p. 1171.
———, 1945a, "North American Geosynclines, Their Classification" (abstract), *ibid.*, Vol. 56, No. 12, Pt. 2, p. 1172.
———, 1947, "Classification of Sections along Allegheny Synclinorium—Chazyan to Trentonian," *chart for private distribution*.
KEITH, ARTHUR, 1894, "Geology of the Catoctin Belt," *U. S. Geol. Survey 14th Ann. Rept.*, Pt. 2, pp. 285–395.
———, 1932, "Stratigraphy and Structure of Northwestern Vermont," *Jour. Washington Acad. Sci.*, Vol. 22, pp. 357–79, 393–408.
KEMP, J. F., 1897, "Preliminary Report on the Geology of Essex County, New York," *New York State Geol. Ann. Rept. 15*, pp. 575–614; also in 1898, *New York State Mus. Ann. Rept. 49*, Vol. 2, pp. 575–614.
———, 1898, "Geology of the Lake Placid Region," *New York State Mus. Bull. 21*, pp. 49–67.
———, AND HILL, B. F., 1901, "Preliminary Report on the Pre-Cambrian Formations in Parts of Warren, Saratoga, Fulton, and Montgomery Counties," *New York State Mus. Ann. Rept. 53*, pp. 17–35.
———, AND RUEDEMANN, R., 1910, "Geology of the Elizabeth and Port Henry Quadrangles," *New York State Mus. Bull. 138*, pp. 7–173.
———, AND ALLING, H. L., 1925, "Geology of the Ausable Quadrangle," *ibid., Bull. 261*. 126 pp.
KIMBALL, J. P., 1890, "Siderite Basins of the Hudson River Epoch," *Amer. Jour. Sci.*, 3d Ser., Vol. 40, pp. 159–60.
KNOPF, E. B., 1931, "Retrogressive Metamorphism and Phylonitization," *ibid.*, 5th Ser., Vol. 21, pp. 1–27.
———, AND JONAS, A. I., 1923, "Stratigraphy of the Crystalline Schists of Pennsylvania and Maryland," *ibid.*, 5th Ser., Vol. 5, pp. 40–62.
———, AND JONAS, A. I., 1929, "Geology of the Crystalline Rocks, Baltimore County," *Maryland Geol. Survey*, pp. 97–199.
———, AND JONAS, A. I., 1929, "Geology of the McCalls Ferry-Quarryville District, Pennsylvania," *U. S. Geol. Survey Bull. 799*. 156 pp.
KRYNINE. PAUL D., 1940, "Paleozoic Heavy Minerals from Central Pennsylvania and Their Relation to Appalachian Structure," *Proc. Pennsylvania Acad. Sci.*, Vol. 14, pp. 60–64.
———, 1946, "The Tourmaline Group in Sediments," *Jour. Geol.*, Vol. 54, No. 2, pp. 65–87.
———, AND TUTTLE, O. F., 1941, "Bellefonte Sandstone: Example of Tectonic Sedimentation" (abstract), *Bull. Geol. Soc. America*, Vol. 52, p. 1918.
KUENEN, P. H., 1937, "The Negative Isostatic Anomalies in the East Indies (with Experiments)," *Leidische Geol. Mededeelingen*, Vol. 8, pp. 169–214.
LESLEY, J. P., 1880, "Slab of Roofing Slate Covered with Casts of *Buthotrephis Flexuosa*," *Proc. Amer. Philos. Soc.*, Vol. 18, pp. 365–66.

MACKIN, J. H., 1935, "The Problems of the Martic Overthrust and the Age of the Glenarm Series in Southeastern Pennsylvania," *Jour. Geol.*, Vol. 43, No. 4, pp. 356–80.
MARSHALL, JOHN, 1937, "The Structure and Age of the Volcanic Complex of Cecil County, Maryland," *Rept. Maryland Geol. Survey*, Vol. 13, pp. 189–213.
MARTIN, J. C., 1916, "The Pre-Cambrian Rocks of the Canton Quadrangle," *New York State Mus. Bull. 185*. 112 pp.
MILLER, B. L., 1935, "Age of the Schists of the South Valley Hills, Pennsylvania," *Bull. Geol. Soc. America*, Vol. 46, No. 5, pp. 715–56.
———, MATHEWS, E. B., BIBBINS, A. B., AND LITTLE, H. P., 1917, "Description of the Tolchester Quadrangle, Maryland," *U. S. Geol. Survey Atlas Folio 204*. 15 pp.
MILLER, RALPH, 1937, "Stratigraphy of the Jacksonburg Limestone," *Bull. Geol. Soc. America*, Vol. 48, No. 11, pp. 1687–1717.
MILLER, W. J., 1909, "Geology of the Remsen Quadrangle," *New York State Mus. Bull. 126*. 51 pp.
———, 1911, "Geology of the Broadalbin Quadrangle, Fulton and Saratoga Counties, New York," *ibid., Bull. 153*. 65 pp.
———, 1916, "Geology of the Lake Pleasant Quadrangle, Hamilton County, New York," *ibid., Bull. 182*. 75 pp.
———, 1917, "The Adirondack Mountains," *ibid., Bull. 193*. 97 pp. (Bibliography.)
———, 1919, "Geology of the Lake Placid Quadrangle," *ibid., Bull. 211–12*. 106 pp.
———, 1926, "Geology of the Lyon Mountain Quadrangle," *ibid., Bull. 271*. 101 pp.
NETTLETON, L. L., 1941, "Relation of Gravity to Structure in the Northern Appalachian Area," *Geophysics*, Vol. 6, No. 3, pp. 270–86.
NEWLAND, D. H., AND VAUGHN, HENRY, 1942, "Guide to the Geology of the Lake George Region," *New York State Mus. Handbook 19*. 234 pp.
PARKS, W. A., 1931, "Natural Gas in the St. Lawrence Valley, Quebec," *Quebec Bur. Mines Ann. Rept. 1930*, Pt. D, pp. 3–98.
PEPPER, J. F., 1934, "The Taconic and Appalachian Orogenies in the Hudson River Region," *Science*, New Ser., Vol. 80, p. 186.
PRICE, P. H., 1931, "The Appalachian Structural Front," *Jour. Geol.*, Vol. 39, No. 1, pp. 24–44.
PRINDLE, L. M., AND KNOPF, E. B., 1932, "Geology of the Taconic Quadrangle," *Amer. Jour. Sci.*, 5th Ser., Vol. 24, pp. 257–302.
RAYMOND, P. E., 1902, "The Crown Point Section," *Bull. Amer. Paleon.*, Vol. 14, pp. 5–44.
———, 1906, "The Chazy Formation and Its Fauna," *Annals Carnegie Mus.*, An. 3, pp. 498–596.
———, 1914, "The Trenton Group in Ontario and Quebec," *Canada Geol. Sum. Rept. of Director for 1912*, pp. 342–51.
———, 1921, "A Contribution to the Description of the Fauna of the Trenton Group," *Canada Geol. Survey Mus. Bull. 31*, pp. 3–64.
REED, J. C., 1934, "Geology of the Potsdam Quadrangle," *New York State Mus. Bull. 297*. 98 pp.
RESSER, C. E., AND HOWELL, B. F., 1938, "Lower Cambrian *Olenellus* Zone of the Appalachians," *Bull. Geol. Soc. America*, Vol. 49, No. 2, pp. 205–48.
RIES, H., 1897, "Geology of Orange County," *New York State Geol. Ann. Rept. (for 1895)*, Vol. 15, pp. 393–475. Also, *New York State Mus. Ann. Rept. (for 1895)*, Vol. 49, Pt. 2, pp. 393–475.
RUEDEMANN, RUDOLF, 1901, "Trenton Conglomerate of Rysedorph Hill, Rensselaer County, New York, and Its Fauna," *New York State Mus. Bull. 49*, pp. 3–114.
———, 1901a, "Hudson River Beds Near Albany and Their Taxonomic Equivalents," *ibid., Bull. 42*, pp 489–587.
———, 1902, "The Graptolite (Levis) Facies of the Beekmantown Formation in Rensselaer County, New York," *ibid., Bull. 52*, pp. 546–75.
———, 1903, "The Cambric *Dictyonema* Fauna in the Slate Belt of Eastern New York," *ibid., Bull. 69*, pp. 934–58.
———, 1904, "Graptolites of New York, Pt. I," *New York State Mus. Mem. 7*, pp. 455–803.
———, 1908, "Graptolites of New York, Part II," *ibid., Mem. 11*. 583 pp.
———, 1921, "Paleontologic Contributions from the New York State Museum," *New York State Mus. Bull. 227, 228*, pp. 116–30.
———, 1925–26, "The Utica and Lorraine Formations of New York," Pt. 1, Stratigraphy; Pts. 2, 3, Systematic Paleontology; *ibid., Bull. 258*. 175 pp.; *idem, Bull. 262*, 171 pp.; *idem, Bull. 272*. 227 pp.
———, 1929, "Alternating Oscillatory Movements in the Chazy and Levis Troughs of the Appalachian Geosynclines," *Bull. Geol. Soc. America*, Vol. 40, No. 2, pp. 409–16.
- ——, 1930, "Geology of the Capital District (Albany, Cohoes, Troy, and Schenectady Quadrangles)," *New York State Mus. Bull. 285*. 218 pp.
———, 1942b, "The Geology of the Catskill and Kaaterskill Quadrangles: Part I, Cambrian and Ordovician Geology of the Catskill Quadrangle," *ibid., Bull. 331*. 247 pp.

SCHUCHERT, CHARLES, 1923, "Sites and Nature of the North American Geosynclines," *Bull. Geol. Soc. America*, Vol. 34, No. 2, pp. 151–229.
———, AND LONGWELL, C. R., 1932, "Paleozoic Deformations of the Hudson Valley Region, New York," *Amer. Jour. Sci.*, 5th Ser., Vol. 23, pp. 305–26.
———, 1933, "Cambrian and Ordovician Stratigraphy of Northwestern Vermont," *Amer. Jour. Sci.*, 5th Ser., Vol. 25, No. 149, pp. 353–81.
———, 1937, "Cambrian and Ordovician of Northwestern Vermont," *Bull. Geol. Soc. America*, Vol. 48, No. 7, pp. 1001–78.
SHERRILL, R. E., 1934, "Symmetry of Northern Appalachian Foreland Folds," *Jour. Geol.*, Vol. 42, No. 3, pp. 225–47.
SMYTH, C. H., JR., AND BUDDINGTON, A. F., 1926, "Geology of the Lake Bonaparte Quadrangle," *New York State Mus. Bull. 269*. 106 pp.
SPENCER, A. C., KUMMEL, N. B., WOLFF, J. E., SALISBURY, R. D., AND PALACHE, CHARLES, 1908, "Description of the Franklin Furnace Quadrangle, New Jersey," *U. S. Geol. Survey Geol. Atlas Folio 161*. 27 pp.
STOSE, G. W., 1909, "Description of the Mercersburg-Chambersburg District, Pennsylvania," *U. S. Geol. Survey Geol. Atlas Folio 170*. 19 pp.
———, 1924, "New Type of Structure in the Appalachians," *Bull. Geol. Soc. America*, Vol. 35, No. 3 pp. 465–80.
———, 1932, "Geology and Mineral Resources of Adams County, Pennsylvania," *Pennsylvania Geol. Survey Bull. C-1*, 4th Ser. 153 pp.
———, 1937, "Structure of the Honeybrook Uplift, Pennsylvania," *Bull. Geol. Soc. America*, Vol. 48, No. 7, pp. 977–1000.
——, 1946, "The Taconic Sequence in Pennsylvania," *Amer. Jour. Sci.*, Vol. 244, pp. 665–96.
———, AND BASCOM, FLORENCE, 1929, "Description of the Fairfield and Gettysburg Quadrangles," *U. S. Geol. Survey Geol. Atlas Folio 255*. 22 pp.
———, AND JONAS, A. I., 1922, "The Lower Paleozoic Section of Southeastern Pennsylvania," *Jour. Washington Acad. Sci.*, Vol. 12, No. 15, pp. 358–66.
———, AND JONAS, A. I., 1923, "Ordovician Overlap in the Piedmont Province of Pennsylvania and Maryland," *Bull. Geol. Soc. America*, Vol. 34, No. 3, pp. 507–24.
———, AND JONAS, A. I., 1927, "Ordovician Shale and Associated Lava in Southeastern Pennsylvania," *ibid.*, Vol. 38, No. 3, pp. 505–36.
———, AND JONAS, A. I., 1933, "Geology and Mineral Resources of the Middletown Quadrangle, Pennsylvania," *U. S. Geol. Survey Bull. 840*. 86 pp.
———, AND JONAS, A. I., 1939, "Geology and Mineral Resources of York County, Pennsylvania," *Pennsylvania Geol. Survey Bull. C-67*, 4th Ser. 199 pp.
STOSE, A. J., AND STOSE, G. W., 1944, "Geology of the Hanover-York District, Pennsylvania," *U. S. Geol. Survey Prof. Paper 204*. 84 pp.
———, 1946, "Geology of Carroll and Frederick Counties," *Maryland Geol. Survey*, pp. 11–131.
ULRICH, E. O., 1911, "Revision of the Paleozoic Systems," *Bull. Geol. Soc. America*, Vol. 22, pp. 281–680.
———, AND SCHUCHERT, CHARLES, 1902, "Paleozoic Seas and Barriers in Eastern North America," *New York State Mus. Bull. 52*, pp. 633–63.
———, AND CUSHING, H. P., 1910, "Age and Relations of the Little Falls Dolomite (Calciferous) of the Mohawk Valley," *ibid., Bull. 140*, pp. 97–140.
VAN INGEN, G., 1902, "Potsdam Sandstone of the Lake Champlain Basin," *ibid., Bull. 52*, pp. 529–45.
WALCOTT, C. D., 1896, "The Cambrian Rocks of Pennsylvania," *U. S. Geol. Survey Bull. 134*. 43 pp.
WHITE, T. G., 1894, "The Geology of Essex and Willsboro Townships, Essex County, New York," *Trans. New York Acad. Sci.*, Vol. 13, pp. 214–33.
WILSON, ALICE E., 1932, "Notes on the Pamelia Member of the Black River Formation of the Ottawa Valley," *Amer. Jour. Sci.*, 5th Ser., Vol. 24, pp. 135–46.
YOUNG, F. P., JR., 1943, "Black River Stratigraphy and Faunas," *Amer. Jour. Sci.*, Vol. 241, pp. 141–66, 209–40.